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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

AUGUST 1975

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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD LECTURE SERIES No. 79

on

Laser Hazards and Safety in the Military Environment

NORTH ATLANTIC TREATY ORGANIZATION

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This Lecture Series No.79, on the subject of Laser Hazards and Safety in the Military Environment, is sponsored by the Aerospace Medical Panel of AGARD, and implemented by the Consultant and Exchange Programme.

The Lecture Series is intended to provide an understanding of the safety problems associated with the military use of lasers. The most important hazard is the inadvertent irradiation of the eye and so the Series will include contributions from the physical and biological sciences, as well as from ophthalmologists. Those involved with laser safety come from many backgrounds – from physics to engineering and from vision physiology to clinical ophthalmology and it is essential that each understands the contribution of the other.

The lectures include an introductory part and from this, the more advanced aspects of each subject are covered, leading to the issues involved in the design of safety codes and the control of laser hazards. The final session deals with medical surveillance of laser personnel. The Series is of value to both military and civilian personnel involved with safety, whether they are concerned with land, sea or airborne laser systems.

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Lecture Series No.79

LASER HAZARDS AND SAFETY IN THE MILITARY ENVIRONMENT

1a

The material in this book has been assembled in support of a Lecture Series presented in Germany (22–23 September 1975), The Netherlands (25–26 September 1975) and Norway (1–2 October 1975) sponsored by the Aerospace Medical Panel and the Consultant and Exchange Panel of AGARD.

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PREFACE

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SAFETY WITH LASERS

by

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The introduction of lasers into both military and civil operations brought with it the problem of the safe use of devices which emit beams of high energy light, and it was not very long before it was only too well appreciated that the eye was well equipped to focus the parallel beam emitted by a laser and so lead to an important hazard. It is now realised that the early assessments of the hazard to the eye were exaggerated, but nevertheless the laser is a device which could seriously impair vision if adequate safety precautions are not taken.

Research directed to the problem of defining the hazard to the eye by high energy monochromatic light and delineating the appropriate safety controls has been an interesting example of many disciplines directed toward a common goal - safety with lasers. Biologists with their knowledge of anatomy have defined the changes in ocular structure caused by lasers which are either absorbed by the transparent media of the eye or by the retina. Biophysicists have defined the energy correlates of damage and physicists have used these data to provide the rules of safety. The contribution of each discipline has been vital and the interaction between disciplines has been essential.

In many ways this lecture series will trace the contributions of these separate disciplines to the solution of the problem. In so doing the more elementary aspects of each subject will be carefully covered and each lecturer will summarise previous contributions essential to understanding his own subject. This will help each student attending the series, whether from the biomedical or physical sciences, to appreciate the importance of each contribution to the overall problem.

The initial lectures will describe lasers and their operation, and the nature of laser radiations. The lectures will also cover the physical terms used in laser work, which are essential to an understanding of the problem, and, particularly, of measurement which is important to adequate safety control. The next group of lectures will deal with the biological effects of lasers and the energy correlates of damage to the eye and skin. These lectures provide the basis for safety codes.

The final lectures deal with the medical surveillance and protection of personnel at risk. This is an area of considerable importance - not least from the medico-legal point of view. Many doctors involved in industry and in the armed services are faced with the problem of providing adequate medical cover, and it is hoped that those responsible for medical supervision of workers in laser environments will add their experience to the series.

It is the aim of the series to provide a forum which will help to create a uniform approach to laser safety within the NATO alliance. To do this we hope that all member countries will participate actively in the discussions.

PROPERTIES OF ELECTROMAGNETIC RADIATION

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SUMMARY

Although the electromagnetic spectrum extends over more than thirty orders of magnitude that portion of it now dominated by the LASER only includes four. It is through this range that all life processes are affected by light, in particular the eye can easily be damaged by it. In this lecture the basic principles dealing with electromagnetic radiation are discussed particularly as they relate to the development of the LASER.

1. INTERACTION OF ELECTROMAGNETIC RADIATION WITH LIVING SYSTEMS.

From the beginning of time the interaction of electromagnetic radiation - light - with atoms, small molecules, and eventually large biologically significant molecules, has led to life on this planet as we know it today. Until this last century there had developed an equilibrium between the flux of radiation from extraterrestrial and from natural sources on the earth and with living systems. Now the ingenuity of man has led to the development of sources of radiation which range from home power frequencies, through radio, radar, infrared, visible, to x-ray which have significant effects upon life processes. Particularly dangerous is the new light source, the LASER, which through the region of the electromagnetic spectrum which includes visible radiation cannot only disrupt biologically significant molecules when the energy contained in the radiation is sufficient to dissociate or ionize them, but which can transfer enough heat energy to biological systems (most vulnerable is the eye) to literally cause them to boil. If sufficient energy is deposited in the system in a very short time a mechanical shock can develop which literally shatters the system much as the impact of a bullet on a window shatters the pane.

In this first lecture, I will discuss the entire electromagnetic spectrum with particular attention given to that part of it that we can see, the visible region, as well as to that part which embraces the far red or infrared, the heat portion of the spectrum, and the far violet, or ultraviolet - the region that we normally associate with suntanning and skin cancer.

Although electromagnetic radiation of all frequencies falls upon the earth, the biosphere in which we live is shielded on the violet end of the spectrum from ultra-violet radiation by an ozone layer of the atmosphere which exists between 22 and 25 kilometers above the earth surface. Such shielding is now perhaps in jeopardy as a result of the pollutants dumped there by supersonic transports and freon from spray cans. Similarly we are not boiled in our own juices, because of the absorption of far infrared radiation by the water vapour in our atmosphere.

Most vertebrates see radiation with wavelengths between 380 and 700 nanometers (1 nm=10^{-9}m=1 millimicron, 10 Å) while the flux of radiation in which they live lies between 340 and 1100 nanometers (nm). Some insects are sensitive to and can see all of this radiation. However, we normally do not consider that man can see in the ultraviolet and infrared, because of the absorption of these radiations in the cornea and eye fluids. However, if the radiation is intense enough, not all of the radiation is absorbed before it reaches the retina. As a result, he can perceive radiation with wavelengths shorter than 300 nm and in excess of 1000 nm. This includes all of that portion of the electromagnetic spectrum where photosynthesis and photobiology take place.

It is not surprising that the powerful new light source, the LASER, has been developed through this portion of the electromagnetic spectrum, since the atomic and molecular processes which make possible LASER action are the same processes involving rotational, vibrational and electronic excitation of atoms, molecules and ions, as are involved in life processes.

As we consider the radiation from various parts of the electromagnetic spectrum and the power available from different sources, it is important that all of us from many fields establish a common reference point - since it is unfortunate that each field encourages a specific set of units that best fits the community. Many of these are hybred and thus even more confusing.

Let me suggest that the MKS (meter, kilogram, second) system be used. To facilitate this, consider the definition and equivalencies for a few things:

Wavelength λ of light in nanometers (nm), 10^{-9} meters is equal to 1 millimicron (mμ)
or 10 Angstrum (Å)

Energy E in joules is equal to 10^7 ergs.

Energy E in electron volts (eV) is equal to 1.6×10^{-19} joules
23.06 kcal/mole.

Power J in watts is equal to joule/second.

2. ELECTROMAGNETIC WAVES

Wave motion in a string, or the ocean, or a soundwave in air is generated by a moving (vibrating) object. Similarly, an electromagnetic wave, like any other wave motion, is developed by periodic motion, this time of an electrically charged particle, e.g., an electron. An electric field naturally exists

around an electron. As it moves and its velocity rapidly changes, an oscillating electromagnetic field is generated, and an electromagnetic wave is produced which has both an electric and magnetic component transverse to the direction of propagation of the wave. In Fig. 1, I show schematically an electromagnetic wave propagating in the z direction with the velocity of light. The wave is plane polarized where both the electric and magnetic vectors oscillate normal to one another and in phase. The plane of polarization of the wave is characterized by the plane in which the E vector lies.

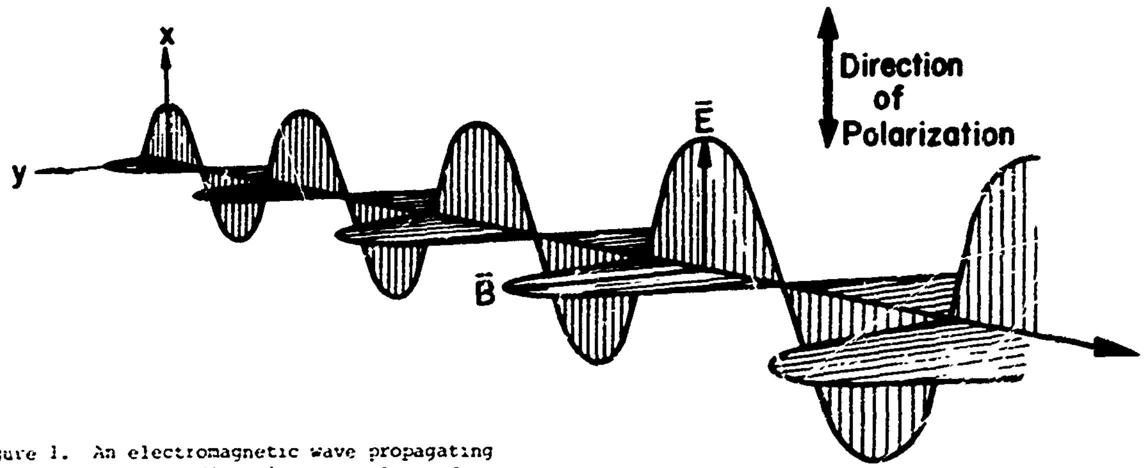

Figure 1. An electromagnetic wave propagating in the z direction and polarized in the x-direction.

The spectrum of electromagnetic radiation is very extensive, reaching from extremely long waves which have wavelengths that are thousands of kilometers long to very high energy cosmic rays with wavelengths much smaller than the diameter of a nucleus, 10^{-15}m. The notion of a classical oscillation of charge as an electromagnetic wave generator breaks down as the wavelength of the emitted radiation approaches the size of the atom, 10^{-10}m. For radiation which includes the visible part of the spectrum we have to consider an atomic or quantum oscillator governed by very special rules. Indeed LASERS are based upon the quantum picture of nature where waves are particles, that is, photons, and photons are waves. For the moment let it suffice to say that within the quantum picture the energy of the photon (a quantum of energy) is directly proportional to the frequency ν of the oscillating charge

$$E = h\nu$$

where the constant of proportionality h is Planck's constant, 6.6×10^{-34} joule sec.

The relationship between the velocity of propagation of an electromagnetic wave in vacuum, c, and the frequency of the oscillation ν (Hertz, Hz or cycles/sec) and the wavelength of the propagated wave λ (meters) is a simple one,

$$c = \lambda\nu.$$

The velocity of light c has magnitude of 3×10 m/sec. Although all other waves require propagation within a medium, electromagnetic waves propagate within a vacuum with a constant velocity throughout the entire electromagnetic spectrum. However, if the EM wave passes through a medium its velocity is changed. The ratio of the velocity of the electromagnetic wave in vacuum and that within the medium, v, is commonly known as the index of refraction of the medium

$$n = \frac{c}{v}.$$

The major part of the EM spectrum is shown schematically in Fig. 2, where we have listed the wavelength in meters, frequency in Hz (cycles per second) and energy of each photon in electron volts (eV), a unit primarily used by the physics community to describe the energy of one electron which has passed through a potential difference of one volt (1 eV = 1.6×10^{-19} joules). One cannot help but be impressed with the enormity of the spectrum which stretches over more than 30 orders of magnitude. Through this entire range the same simple laws organized by Maxwell in the late 1800's describe the entire electromagnetic spectrum. Notice that out of the entire spectrum the visible portion which largely governs life processes and visual communication is very narrow indeed.

3. EMISSION AND ABSORPTION OF RADIATION BY QUANTUM OSCILLATORS

By the turn of the century the stage was set for Planck and Einstein to recognize the importance of the quantum oscillator. In order to describe the distribution of EM radiation that was given off by hot bodies. Planck had to propose that the radiation that was emitted came in bundles of energy, quanta, instead of coming as continuous waves. Man finally recognized the dual particle-wave nature of matter. For a particular hot body in which radiation and absorption is in complete equilibrium, that is for a blackbody radiator, Planck showed that for an infinite number of quantum oscillators each with a different frequency ν, the energy density of the radiation between ν and ν+dν is U_ν which for a system in thermal equilibrium at an absolute temperature T°K is given by Planck's law:

$$U_\nu \, d\nu = \frac{8\pi h\nu^3}{c^3} \frac{d\nu}{[\exp(h\nu/kT)-1]}.$$

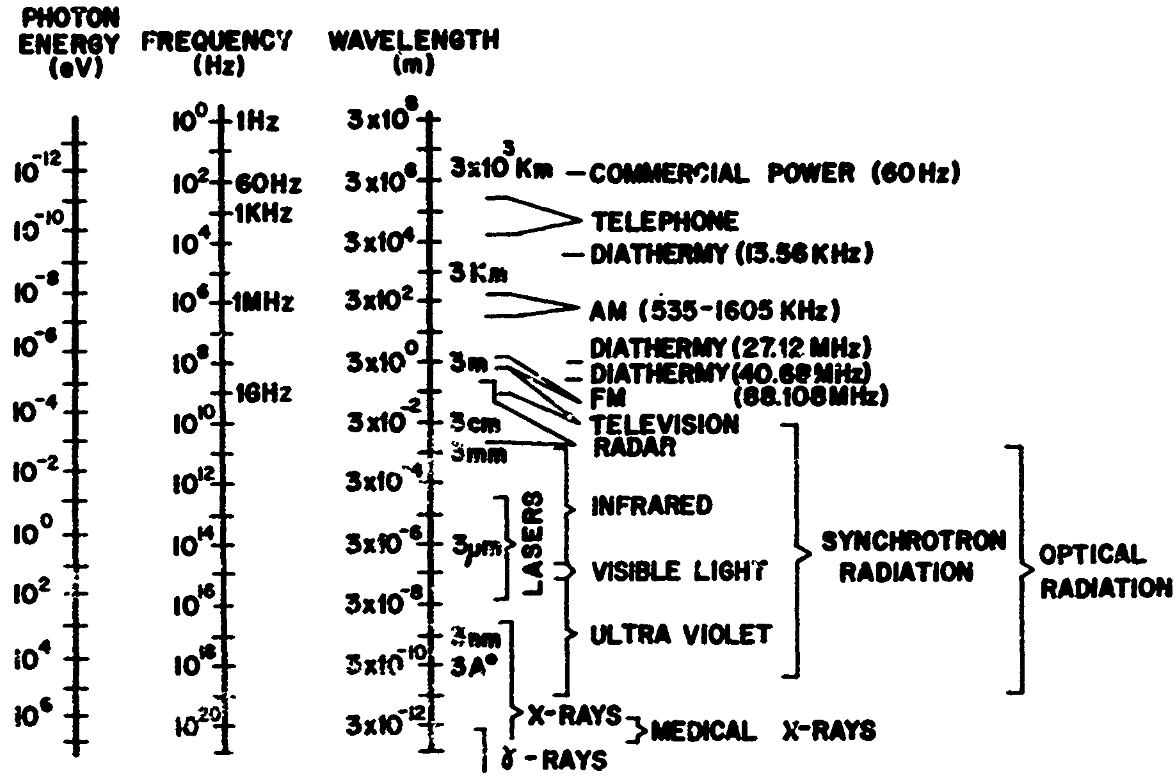

Figure 2. Electromagnetic spectrum showing the various Spectral Regions.

Here $k = 1.38 \times 10^{-23}$ joules/^{O}K is Boltzmann's equilibrium constant. The expression states that there are $\frac{8\pi\nu^2}{c^3}$ degrees of freedom in the system of oscillators with an average energy $h\nu[\exp(h\nu/kT)-1]$ per degree of freedom at temperature T.

If one considers a hole cut in the wall of the blackbody cavity, the radiant power emitted normal to the emitting surface per unit area of the emitting surface per wavelength often called the spectral radiant emittence of the blackbody can be expressed equally well in terms of a wavelength interval between λ and λ-dλ

$$W(\lambda,T)\,d\lambda = \frac{C \quad d\lambda}{\lambda^5\ [\exp(hc/\lambda kT)-1]} \quad \text{watts/m /nm.}$$

if the wavelength λ is given in nanometers (nm) and $C = 3.74 \times 10^{25}$ watts nm^4/m^2. It follows then that one can define the spectral brightness of a source as the spectral radiant emittence normal to the emitting surface contained in a small cone or solid angle dΩ steradians around the normal. This quantity is plotted in Fig. 3 for the blackbody radiator with a temperature which varies from 100^{O}K through to 10 million degrees K, a range which was unrealistic to consider at the time of Planck, but which now includes the temperature of the corona of the sun, approximately 6000^{O}K, the temperature for nuclear fusion about $10^{8\,O}$K and the equivalent temperature of a high energy synchrotron radiation source (radiation from highly relativistic electrons) approximately 10 million^{O}K. I mention this latter source since synchrotron radiation sources which emit a very intense continuum from the infrared through to the x-ray region are rapidly developing as research tools in many parts of the world.

From the Planck radiation formula it follows that the wavelength associated with the distribution maximum λ_m times temperature is a constant,

$$\lambda_m T = 2.9 \times 10^6 \text{ nm}^{O}\text{K}.$$

which is the well known Wien's displacement law. This relation was identified empirically before Planck's work. In a similar way, one can derive the Stefan-Boltzmann law for the total power radiated by a blackbody through the surface of the area emitter summed over all wavelengths

$$W_t = \int_0^\infty W(\lambda,T)\,d\lambda = \sigma T^4$$

Most radiation emitters, with the exception of the LASER, are not as intense as blackbody radiators, therefore the blackbody curves represent the upper limits of power emitted from a surface. Many solids and some gas discharges radiate like an idealized blackbody. In fact, the spectral distribution emitted by incandescent lamps, and high density arcs and stars can be calculated to a good approximation from Planck's formula. As a reference point, a blackbody at a temperature of 5200^{O}K has its radiation peak at

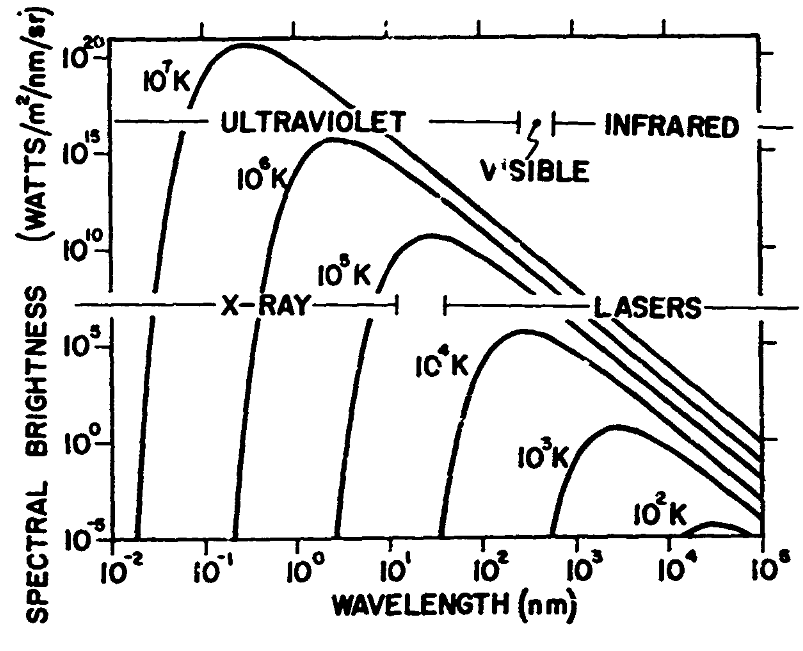

Figure 3. Spectral brightness for the blackbody radiator as a function of temperature.

556 nm near the centre of the visible spectrum, where the human eye is most sensitive. Yet only 40 percent of the radiation falls within the visible part of the spectrum, six percent in the ultraviolet and the rest in the infrared.

There is yet another quantum process which was important in establishing the particle nature of light - the photoelectric effect. It was observed that electrons were removed from a metal surface only when the energy of the photon was equal to or greater than the binding energy ϕ of the electron in the metal,

$$KE\ (\text{electron}) = h\nu - \phi\ .$$

Any excess energy went into the kinetic energy KE of the outgoing electron. It is only since the advent of LASERS that it is realistic to consider what happens when many photons of insufficient energy to release an electron arrive at the same time. Now multiphoton excitation and ionization processes (that is, non-linear processes) are commonplace.

Once the concept of the quantum oscillator was recognized it followed directly that atoms with negative electrons moving around positively charged cores did not continuously emit light, instead light was spontaneously emitted only when the electron made a quantum jump from a higher level of the atom E_2 to a lower one E_1 (refer Fig. 4a). If $h\nu$ equal to the energy interval shines upon state 1, the light can be absorbed (Fig. 4b) thus exciting the system, the frequency of the light is given by

$$\nu_{21} = (E_2 - E_1)/h$$

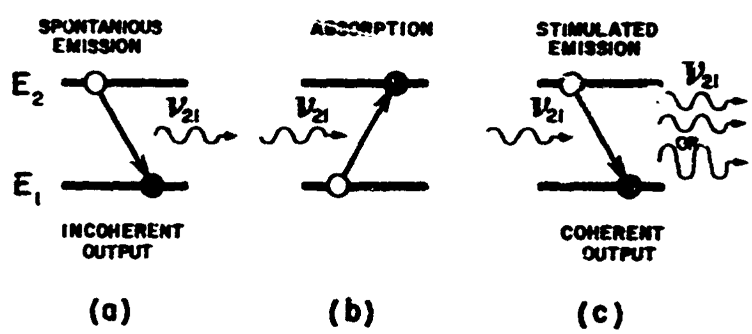

Figure 4. Three modes of operation for the quantum oscillator a) Spontaneous emission of a photon of frequency ν_{21} b) Photoabsorption and c) Stimulated emission of ν_{21}.

Rules known as selection rules govern the transition probability between states 2 and 1. The time on the average it takes τ_{21} for a transition to occur is the radiative lifetime of the excited system. In the case of molecules one must not only consider the electronic transitions but transitions from one state of vibration of the molecule to another, and a state of rotation of the molecule to another. The principal terms describing the energy level of the system including electronic vibrational and rotational energy are

$$E_{nvJ} = E_n + E_{v_n} + E_{J_{nv}}$$

where n is the electronic level, v_n a particular vibrational level within the electronic state and J_{nv} the rotational sub-level.

It is important to keep in mind the relative magnitude of the intervals which exist between energy levels. Normally pure electronic transitions give rise to electromagnetic radiation which appears in the near infrared, visible and ultraviolet portions of the spectrum. This corresponds to energies between a fraction of an electron volt to tens of eV. Pure vibrational transitions however occur in the red to infrared region, while rotational transitions are dominantly in the infrared. It is these transitions which are the basis of radiation from LASERS.

When an atomic system is forced to make a transition from E_2 to E_1 (Fig. 4c) by light of frequency ν_{21}, the light that is emitted tends to be in the same direction as that of the stimulating light so that the intensity of the emitted radiation adds in phase or constructively to that of the stimulating light. It is just this process of stimulated emission which makes possible the formation of optical radiation which is intense, monochromatic, and in phase rather than being randomly distributed in time as is the case when a number of quantum oscillators randomly decay in their own time. Such organized radiation sources have long existed in the power, radio, television and radar portions of the EM spectrum but only with the advent of the LASER has it been possible in the optical part of the spectrum as well.

4. LASER PROCESSES

Consider the usual relation which describes the attenuation of a beam of radiation passing through an absorptive medium. This is the familiar exponential relationship (Beer's Law)

$$I(x) = I_o \exp(-\alpha x)$$

where $I(x)$ is the intensity at a distance x of a light beam originally of intensity I_o after passing through the optical medium of optical thickness αx. α is the absorption coefficient, which can be written in terms of the Einstein coefficient for the absorption of light, B_{12}, and the stimulated emission of light, B_{21}, simply

$$\alpha = N_1 B_{12} - N_2 B_{21}$$

where N_1 and N_2 are the number densities of atoms in the lower state 1 and the excited state 2. Since the probability of absorbing the radiation or stimulating its emission are equal, $B_{12} = B_{21} = B$, it follows that

$$\alpha = B(N_1 - N_2).$$

Anyone from 1917 onward could have readily observed that α can be made negative if N_2 is greater than N thereby causing $I(x)$ to grow larger than I_o the original intensity as x increases. This possibility is called negative absorption or amplification. In other words, amplification of the radiation only occurs when the number density of particles in the higher lying excited state 2 exceeds that in state 1. This situation constitutes population inversion. Although the process was extensively studied through the 20's and 30's the invention of the LASER, light amplification by stimulated emission of radiation both as a light source and light amplifier did not occur until the late 50's.

There are many ways of establishing a population inversion in gases, liquids and solids. This will be discussed in lecture 2 along with more details associated with various types of LASERS. For the moment let it suffice to say that for laser action to occur an amplifying medium must be artificially produced and that this medium must be set in an optical cavity (Fig. 5a) bounded on each end by mirrors, one of which is 10 - 90 percent transparent. This will allow the stimulating photons to resonate many times through the medium in order to cause the maximum allowed depletion of the excited atoms. The radiation will be amplified (Fig. 5b) on each pass through the system as long as the system remains in an inverted state. If the gain per pass of the radiation is greater than the total loss per pass, then the system will be made to lase.

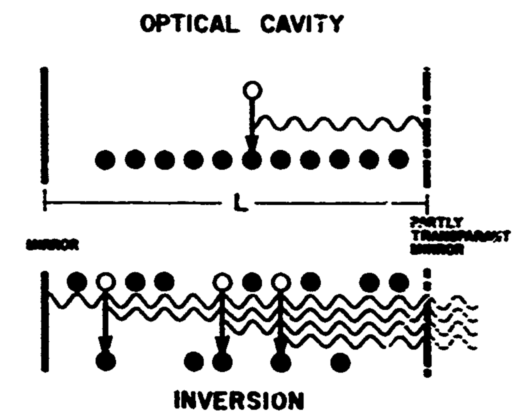

Figure 5. Shown in a) is the optical cavity with the medium slightly excited. In b) there is a marked population inversion. Some levels are stimulated to emit.

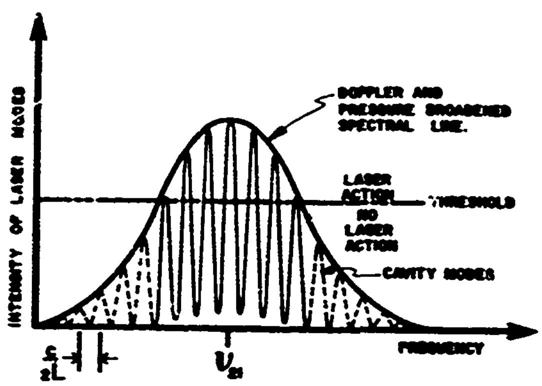

Figure 6. Spectral line centered at ν_{21} showing seven normal cavity modes with intensities which exceed the threshold for laser oscillation.

Since normally each atom prefers to be in its lowest energy state, an external source of energy is required to maintain an inverted system. It is not sufficient that this external energy source slightly disturb the Boltzmann (thermal) equilibrium, it must develop population inversion. This process is called pumping. As long as pumping continues the inversion is maintained. If the pump should be stopped the atoms will rapidly return to an equilibrium between states through the process of spontaneous and

stimulated emission, and lasing action will cease.

We have seen that the frequency of the laser light is limited to a narrow band centred around ν_{21} associated with the spectral width of the transition 21. This width includes the width due to the natural decay of the excited state, the motion of the radiating atoms and pressure broadening. However, within this broad band of frequencies the LASER radiation is even more restricted by the properties of the optical cavity. Atoms which oscillate in phase with one another in the cavity are said to be in normal modes. The frequencies of the normal modes of the free oscillations are harmonics of the fundamental frequency ν_{21}, Fig. 6. Within the optical resonating cavity of length L, standing waves similar to those in a string occur only for wavelengths which are an integral number of one-half the emitted wavelength λ, so that

$$L = m\,\lambda/2 \qquad m = 1,2....$$

From the simple relationship between the velocity of light, wavelength and frequency discussed above, the frequency interval between adjacent modal lines is

$$\Delta\nu = c/2L$$

If for example for red light where ν_{21} is approximately 5×10^{14} Hz (as for He-N_2 red laser light) and an optical cavity of length 1 meter, then the number of modes that exist in this case is 3×10^6. In other words the radiation which had a line width associated with the atomic transition plus doppler shifting plus pressure broadening is now divided into nearly three million parts only some of which will show LASER action because they meet the necessary inversion criterion. The spectral width of each of these lines associated with the normal modes of oscillation of the cavity is at least a million times narrower than the original spectral line. It is reasonable then to imagine that in the case of 5×10^{14} Hz radiation with a normal line width $\sim 10^6$ Hz, Fig. 6, the line width associated with the excitation of a simple mode can in principle if not easily in practice be made 1 Hz, thus the spectral brightness or the amount of power available per unit area of emitter within one steradian at a given wavelength or frequency is extremely large, in fact larger than any other source.

Normally we also consider the spatially distributed modal pattern from a cylindrical or a rectangular cavity. This pattern is quite complex containing many transverse electromagnetic modes TEM_{mn} the details of which are beyond the scope of this lecture. In the designation of modes m and n are integral values where for circular mirrors n denotes the order of angular variation and m the order of radial variation. TEM_{oo} is usually the dominant mode in most cavities.

5. PROPERTIES OF LIGHT SOURCES

The special properties of the radiation produced from laser action will become clear as we compare the LASER as a light source with other sources of electromagnetic radiation:

a. Point sources and extended sources - Although all light sources have finite dimensions it is useful idealization to consider a source as a point, even though there is no true point in nature. For example, an atom has its extension and stars which appear to us as points in reality are very large. The light from a point source differs from that of an extended source in that it propagates radially from its origin. Close to the source most of the rays intercepting the small surface area A strongly diverge, however as that same surface area is moved off at a large distance, divergence is minimized and the light can be considered collimated.

An extended source by contrast can be considered as made up of a large number of point sources. Close to this source, the light rays passing through the test area A have a larger divergence than those from a point; however, as A is moved off to a very large distance, often referred to as infinity, the light behaves like it comes from a point source. Unlike most other extended light sources the LASER because of the organized nature of its radiation can be considered as a point source, even though in reality it is not.

b. Monochromaticity or Temporal Coherence - A few years ago one would have called the light from a mercury arc lamp monochromatic. However, when this light is viewed through a spectroscope one finds it made up of approximately five lines with the dominant line in the blue. Since the advent of the LASER the spectral width of the blue line is reduced by more than a million so that the light for the first time can truly be considered monochromatic.

c. Spectral Coherence of Light - Light from a point source has a very special quality, spatial coherence. If light could be emitted from a point source, anywhere on a sphere surrounding the source, the electromagnetic wave would show the same maximum or minimum in its intensity. This light is coherent. As one backs away from the point to infinity, the light reaching the observer remains in phase or in step.

In the case of LASER the very process of stimulated emission which produces the amplification of the light leads to the emission of radiation in which all the waves moving in one direction are in step or in phase, quite similar to the situation one observes from a point source at infinity. The coherence of laser light then is one of its most important properties.

The coherence of LASER light is best observed through interference and diffraction effects. They involve the constructive and destructive interference interaction of the electromagnetic waves. Interference effects can most clearly be demonstrated with monochromatic, coherent light from a LASER. In fact, interference photography, holography, is only realistic with the LASER as a light source.

Consider the case of diffraction from a narrow slit of width d. In Fig. 7, I show monochromatic coherent light coming from the left, illuminating the slit. On a screen some distance away is the diffraction pattern. The position of the maxima where there is constructive interference of the waves is given by the

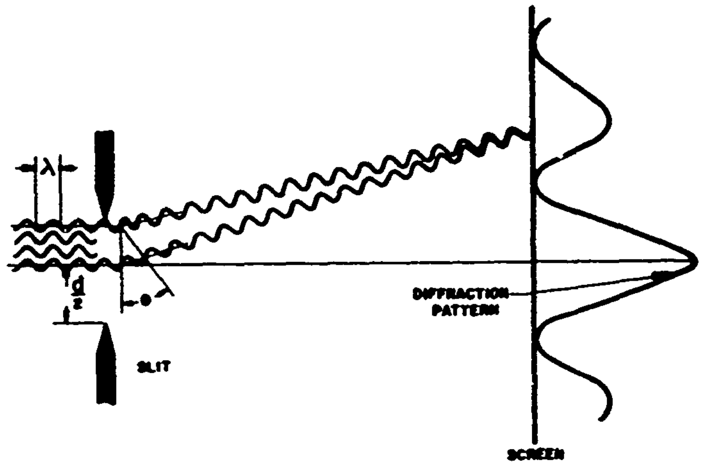

Figure 7. Single slit diffraction pattern

simple formula

$$n\lambda = (d/2)\sin\theta$$

where n (known as the order) is the number of full wavelengths that a wave coming from a point source in the middle of the slit is shifted so that at the screen it constructively interferes with one from the upper or lower edge. θ is the angle between the direction of the collimated rays and the point of observation on the screen. From an examination of the figure, one can readily see that if the light were not coherent at the slit (that is, the waves were out of phase), and many wavelengths were involved, no diffraction pattern could be recognized at the screen.

d. Polarization of Light - Electromagnetic radiation may be polarized in a number of ways. In the case of radiowaves which are produced by the motion of electrons up and down an antenna the wave is by nature polarized. In Fig. 1 this would be along the direction of the $\bar{E}$ vector. Normally light which is generated by very many atomic oscillators each acting independently is not polarized. However, it can be made so by reflection, as for example reflection of sunlight at an angle near 50° from the surface of a lake; or the back scattering of sunlight from the molecules in the air. Such scattering is known as Rayleigh scattering. Within our common experience we find that polaroid sunglasses eliminate the enormous glare associated with such processes.

The radiation normally obtained from a gas LASER is also polarized, not because of some basic atomic process but because the exit window of the LASER is mounted so that the beam axis is approximately 50° with respect to the normal to the exit window. At Brewsters angle only radiation which is polarized will build up within the laser cavity. As a result the light which is emitted is highly polarized.

6. GENERAL DEFINITIONS AND COMPARISONS BETWEEN LASERS AND OTHER SOURCES

LASERS vary considerably in output power from a few thousandths of a watt as in the case of the very useful (red) helium-neon gas laser to the order of terawatts in the Q-switched (fast pulsed) carbon dioxide-gas (infrared) laser. Some LASERS are capable of operating continuously (cw) while other types of LASERS are operated in a pulsed mode. In the discussion which follows, we will compare a helium-neon cw gas laser with a power of one milliwatt with other light sources.

a. Divergence and diffraction limit - Because of diffraction any beam of light emitted from a source with a small cross-sectional area diverges with a minimum half-angle of divergence θ given by the ratio of the wavelength to the diameter of the beam, λ/d. This follows directly from the single slit diffraction equation discussed in the previous section. A beam of light having this divergence is said to be collimated to within the diffraction limit. Once again because of the monochromaticity and coherence of LASER light its divergence is ideally that set by this limit. On the other hand light from other extended sources, because the light is neither monochromatic nor coherent, has a divergence that is considerably larger. One of the best and most dramatic examples of this is in the now classic picture of the partially eclipsed earth as seen by the T.V. camera of surveyors where two low power argon ion laser beams (in the green) can be seen eminating from a region in the western part of the United States while none of the light from the major centres in the West can be seen at all.

The approximate 600 nanometer red light from helium-neon LASER with the output diameter of 2 mm has a half-angle divergence θ approximately equal to 3×10^{-4} radians, or 0.0167^{c}. Consequently, one can consider the beam produced by a point source located some distance behind the exit mirror of the oscillating cavity. The laser equivalent point source radiates energy only within the cone 2θ while the brightness of this extended source is very high in the direction of the beam it is zero at other angles, which are outside the cone 2θ.

b. Radiant Power, radiant emittence and intensity - A point of coherent source is measured by its radiant power, the measure of energy it emits in a unit time in all directions. Radiant emittence is the radiant power emitted normal to the emitting surface per unit area of the emitting surface. The intensity is the radiant power per unit solid angle.

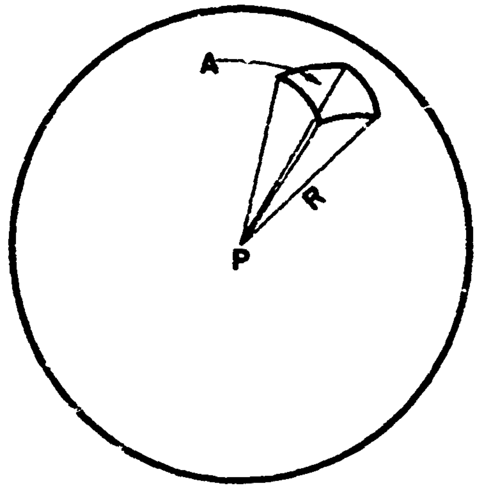

Figure 8. Sphere showing the elements defining solid angle.

Consider a sphere of radius R around a point source which has some closed area on the surface, as shown in Fig. 8. The area on the surface divided by the radius R^2 of the sphere is the definition of the solid angle ($\Omega = A/R^2$) measured in steradians (Sr). Since the entire surface area of the sphere is $4\pi R^2$ it is clear from the definition that 4π steradians represent the maximum solid angle around a point source. If we consider a fixed area like the size of the cornea of the eye, as one moves away from source the intensity of the light which enters the eye decreases as $1/R^2$ since the solid angle subtended from the point source changes as $1/R^2$. This is what is normally called the inverse square law which governs many of the basic physical principles of nature.

It can be easily demonstrated that for the LASER, the solid angle into which the power is emitted from a point source is equal to $\pi\theta^2$. Since for our He-Ne LASER θ is equal to 3×10^{-4} radians, and if the power is 1 milliwatt, it follows that

$$\text{Intensity} = \frac{10^{-3}}{\pi\,(3 \times 10^{-4})^2} \approx 4 \times 10^3 \text{ watts/Sr.}$$

c. Brightness - The brightness of an extended source is the radiant/emittence/unit solid angle or the intensity/unit area of the emitter. Both intensity and brightness fall off as cos θ the angle with respect to the normal to the emitting surface. If in the case of the 1 milliwatt LASER the radius of the beam is 1 mm or 0.001 meters,

$$\text{Brightness (LASER)} = \frac{4 \times 10^3 \text{ watts/Sr}}{4\pi\ (0.001)^2 m^2} = 3 \times 10^8 \text{ watts/m}^2\text{/Sr}$$

By comparison, for various other light sources:

Brightness (Tungsten filament @ 3300°K) = 7×10 watts/m²/Sr

(High power carbon arc) = 3×10^6 watts/m²/Sr

(Sun) = 2×10^7 watts/m²/Sr

(0.25 MW Synchrotron radiation source) = 1×10^8 watts/m²/Sr

Thus, the smallest of lasers, is brighter than all known light sources; in fact it is two orders of magnitude brighter than the sun, the source of all life on this planet.

d. Spectral Brightness - We have already spoken of spectral brightness as it relates to a blackbody radiator. Once again it is defined as the brightness of a source per unit wavelength or frequency.

There is no comparison between the amount of power in the form of light which can be delivered from an He-Ne 1 milliwatt LASER and a 10^4 watt carbon arc radiating in the same small slice of the total emission spectrum. Although 10 million times more total optical power is delivered from the arc the amount of power in a small spectral band is much larger for the helium-neon LASER. For the arc lamp the power is distributed over approximately an interval of 500 nanometers, therefore, we have 10,000/500 = 20 watts/nm. However, in the case of the helium-neon LASER, which as we pointed out before could be made to have a frequency width as narrow as one Hertz by the choice of a single mode (1 Hz at the wavelength of the helium-neon laser 600 nm corresponds approximately to a special line width of 1×10^{-12} nm), the power per unit wavelength is equal to $10^{-3}/10^{-12}$ or 10^9 watts/nm. In other words the amount of light available in a narrow spectral band is much larger from a laser than from any other light source.

e. Illumination at a distance - Although it is possible to photograph the light from the argon-ion LASER on the moon, is it realistic to imagine that lasers can be used to light the surface of the moon? Let's look at this problem. A distant surface subtends a very small solid angle at the source. Therefore one wants a source that emits a great deal of light into a small solid angle, and that is just what a LASER does. Let us compare the amount of light which the 1 milliwatt LASER can bring to a distant surface, A, with the amount coming from the same surface from a Tungsten filament at 100 W incandescent lamp. Since the lamp radiates 100 watts into the entire sphere of area 4 R the power reaching the area A on the sphere is given by

Power = Intensity x Solid Angle

$$\text{Power (Tungsten Bulb)} = \frac{100 \text{ (Watts)}}{4\pi\text{(Sr)}} \times \frac{A}{R^2}\text{(Sr)}$$

$$= 8\ A/R^2 \text{ watts}$$

distributed over the entire visible spectral range. From above,

$$\text{Power (He-Ne Laser)} = 4 \times 10^3 \text{ watts/Sr} \times \frac{A}{R^2}\ \text{(Sr)}$$

$$= 4 \times 10^3\ A/R^2 \text{ watts.}$$

in a single spectral line. It follows then that the ratio of the powers reaching a small area A is

$$\frac{\text{Power}_A\text{(He-Ne Laser)}}{\text{Power}_A\text{(Tungsten Bulb)}} \sim 500$$

When one remembers that LASERS have been developed that are a thousand-million-million times more intense than our helium-neon laser one recognizes the enormous potential for the transfer of energy and information available through the LASER.

In Section 3 we showed that the brightness of even the smallest helium-neon LASER is in excess of that of the sun. Does this mean that the LASER placed as far away as the sun could do a better job than the sun in illuminating the earth? Of course not! The power of each is its brightness times the solid angle subtended times the area of the emitting surface. Under these circumstances one sees that

$$\frac{\text{Power (Sun)}}{\text{Power (Laser)}} \approx \frac{2 \times 10^7 \text{ watts/m}^2\text{/Sr} \times \pi(10^{11})^2 \times A/R^2 \text{ (Sr)}}{3 \times 10^6 \text{ watts/m}^2\text{/Sr} \times \pi(10^{-3})^2 \times A/R^2 \text{ (Sr)}} \approx \frac{6 \times 10^{25} A/R^2 \text{ watts}}{9 \times 10^2 A/R^2 \text{ watts}}$$

$$\approx 7 \times 10^{22}$$

Even though the sun is a source of lower brightness than the LASER its very large area more than makes up for it.

f. Concentration of power into a small area - Though it won't be proven here, radiant power density at a point or some area which is being illuminated by a source depends only upon the brightness of the source. In this case the size of the source is immaterial. Furthermore, the power per unit irradiated area has a value which is the same order of magnitude as the brightness. Since the laser has the greatest brightness of all light sources, it follows that the laser is capable of producing a greater power density than any other sources.

As one might expect the smallest area into which radiation in a parallel or nearly parallel beam can be focused by a lens is limited by diffraction to an area of approximately λ^2 where λ is the wavelength of the radiation. The highest power density produced by 1 milliwatt LASER is thus given by a power output divided by λ^2 or

$$\text{Power Density He-Ne (LASER)} = \frac{1 \times 10^{-3} \text{ watts}}{(600 \times 10^{-9})^2 \text{m}^2} = 3 \times 10^9 \text{ watts/m}^2$$

Note that the value for the power density is within an order of magnitude of the brightness of the LASER. Remember again that this particular LASER is one of the lowest power LASERS. Therefore, as one might expect the effectiveness of more intense LASERS like a 6000 watt CO_2 cw LASER for the machining of metals, welding and other such purposes, is extremely good. Another impressive example is a picture of approximately ten burns in one hemoglobin cell caused by the light of a ruby LASER focused onto the cell. Microsurgery using LASERS is now a reality.

Although LASERS are far better than any other man-made sources for many purposes, they are not the solution to all problems. Other light sources are far superior to the LASER for many purposes such as general illumination. The applications of LASERS will be discussed in the next lecture.

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LASERS

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SUMMARY

Principles and properties of the LASER are discussed in some detail together with a description of the various types of LASERS and their applications.

1. MORE ABOUT LASER PROPERTIES

The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation.

Several years after the Russians Basov and Prokhorov[1] and the Americans Gordon, Zeiger and Townes[2] had shown that stimulated emission of radiation at microwave frequencies could be accomplished with the ammonia molecule in preselected states, Schawlow and Townes[3] proposed that such amplification could occur in the infrared and throughout the entire optical region.

In order to maintain amplification, we must cause the system to be sufficiently excited so as to have a net round trip gain for the radiation in the laser cavity at least equal to unity. However for oscillation to build up over and above the spontaneous emission, the net round trip gain must be greater than unity. This leads to the development of the minimum inversion necessary for laser action. The relationship describing this is known as the Schawlow-Townes criterion. If one assumes that the shape of the radiation line is Lorentzian (somewhat bell shaped as in Fig. 6, Lecture 1) it follows that

$$N_2\frac{g_2}{g_1} - N_1 \geq \frac{8\pi c}{\lambda^3}^2 \frac{\Delta\nu}{\nu}\frac{\tau_2}{\tau_c} = \Delta N_c$$

where N_c is the critical population inversion density necessary to maintain laser oscillation. In the expression N_2 and N_1 are the population densities for states 2 and 1 while g_2 and g_1 are the degeneracies associated with each of these states. $\Delta\nu$ is the half width of the broadened spectral line, while τ_2 is its natural half-life and γ_c is the lifetime characteristic of the cavity construction. One sees immediately that as the energy interval between levels increases, that is, as the wavelength decreases, the necessary critical population inversion density increases rapidly. Similarly as the lifetime of the radiative state increases so too does the necessary critical population inversion density. However, there is advantage in using states for the upper laser level with very long lifetimes, since atoms decaying from still higher levels may be trapped in the lasing level, thus increasing the density of excited atoms.

Many materials can now be made to lase, not only in the infra: .. but the visible and near ultraviolet regions of the electromagnetic spectrum as well. There appear to be serious limitations to developing a far UV or x-ray LASER but serious study suggests the γ-ray lasers may yet be developed[4].

Using the above mentioned criterion for minimum inversion ΔN_c necessary for laser oscillation, for a ruby system which will be discussed in greater detail later one can estimate that the ruby rod 10cm in length can be made to amplify radiation if the population of the upper level exceeds that of the ground level by as little as 0.7%. Since the concentration of chromium ions Cr^{3+} in pink ruby is 1.6×10^{19} atoms/cm^3, states 1 and 2 each contain approximately 8×10^{18} atoms/cm^3, and the population difference must be approximately 5.6×10^{16} atoms/cm^3.

The formulation described above was developed in association with a model two-level laser system; however, most solid state LASERS like the pink ruby system are three, while most others are four level LASERS like neodymium doped systems. As a result the simple criterion is only a rough approximation. Exact analysis of a system requires that one solve a series of rate equations associated with the total number of excited atoms in which the ratio of populations in various states under stationary conditions can be derived. If indeed the system is excited by a blackbody radiator, one then can also calculate the power of optical pumping radiation necessary to cause and maintain an inversion. It follows then that one can calculate the equivalent minimum source temperature capable of producing adequate illumination in the spectral energy interval where, for example, the ruby absorbs. For the ruby rod discussed above the necessary blackbody temperature of the pumping light source must be at least 3300°K. In reality it must be higher because of other complicating factors. However, this is realizable today.

The primary method used for laser pumping is the intense flashlamp (Fig.1) which normally is mounted along with the laser cavity in a geometrical system of mirrors that effectively focuses all the optical energy on the solid, liquid or gas in which the inversion is to be produced. Often inversion can be produced in gas discharges through any one or more of a number of processes which include direct and resonance excitation, energy transfer and dissociation. In what is now known as a CHEMICAL LASER, inversion is brought about through the chemical reaction involving several atoms and molecules or in ion systems through electron excitation or charge transfer. In semi-conductors, the applications of strong electric fields across the junction can cause inversion as can the bombarding of the semi-conductor with an external beam of electrons. Similarly in high-pressure gases high power in the visible and near ultraviolet can be produced with the aid of a very high energy, high current electron beam.

2. MODES OF OPERATION

Many LASERS, particularly low powered LASERS can be made to operate in a continuous wave (cw) mode where power is continuously added to the system to maintain the inversion at the same time light is extracted from it. As more power is extracted from the system the light will tend to oscillate. The natural pulsation reflects the repeated breakdown

natural pulsation reflects the repeated breakdown of the minimum inversion criterion for laser oscillation caused by the depletion of the excited state due to laser action, or focusing effects on the light beams due to the change in the optical properties of the medium during operation. These regular pulsations of the LASER are disturbing for most applications, especially communication where the timing and the control of the intensity envelope are particularly important.

Often LASERS are intentionally worked in a pulsed mode. This is brought about by pulsing of the optical radiation or the discharge, or the electron beam or the electric field. The length of the light pulse from the laser may not correspond to the length of time the exciting radiation is on since once the system begins to lase often inversion can no longer be maintained. Also, any change in the focusing properties of the medium can cause oscillation to be quenched.

Since the LASER is an oscillator, consisting of an amplifier with a feedback device, the threshold condition of oscillation is reached when the gain of the amplifier is greater than the sum of the losses. The loss rate of the system is frequently described by the quality factor Q. As Q decreases the loss increases, therefore the ΔN_c necessary for the oscillation to begin also increases. Because of this relationship, the technique used to hold back the onset of oscillation by temporarily increasing the losses in the LASER is called Q-switching or Q-spoiling. For efficient production of a single giant pulse, it is essential that the Q-switching process be fast in comparison to the lifetime of the photon within the cavity, hence the time of switching between low and high Q can be chosen so as to assure the development of the greatest possible inversion in the material.

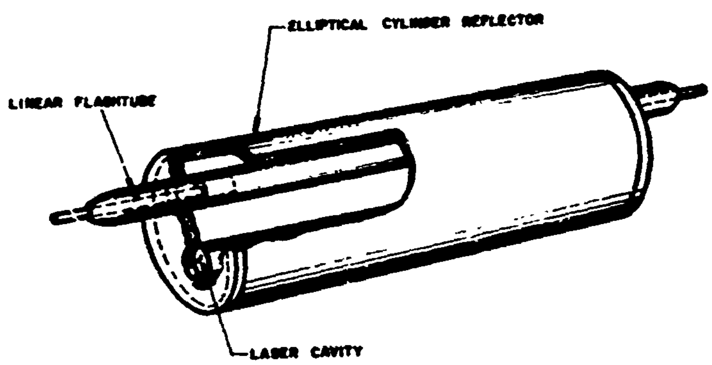

Figure 1. One of many laser configurations. The laser cavity is usually defined by mirrors at each end, one of which is semi=transparent.

In general the principle of Q-switching consists of inserting a switch (Fig.2) into the laser cavity. This switch can be activated during the pump pulse in such a way that it separates the pumping proper from the laser action. The energy stored in the cavity can then be made very high to be released in one single giant pulse. Since tremendous loss occurs during pumping, the total output energy released during the Q-switching mode is normally less than that of the normal mode of operation. However, since the pulse is very short the power output is tremendously increased. For example, values in excess of Terawatts(10^{12} watts) corresponding to an energy release greater than 100 joules are now common.

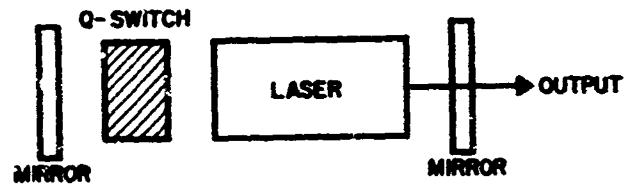

Figure 2. Schematic representation of a Q-switched laser system. In some systems the switch and mirror are combined.

McClung and Hellwarth[5] in 1963 were the first to produce giant pulses with the ruby LASER. They used an optically active Kerr cell as a shutter, making use of the preferential polarization of the laser light and the rotation of the plane of polarization of the light when the Kerr cell was activated.

Mechanical switching has existed from the very beginning. The idea of employing a rotating chopper wheel to open and close the optical path between the active medium and one of the mirrors was first used by Collins and Kisliuk in 1962,[6] however this method is inherently slow. Tens of microseconds have elapsed from the time the chopper slot first begins to expose the active medium until the medium is fully exposed. Faster mechanical switching may be accomplished by rotating one of the mirrors, or by replacing one of the mirrors with a rotating total-reflecting prism.

A much simpler, and more effective Q-switch uses a dye solution which bleaches within ns when the impinging intensity surpasses a minimum value and becomes completely transparent. The dye must have two energy levels, which are separated by an energy equal to that of the laser photon. When the laser light is absorbed by the dye molecule, all electrons from the lower level are lifted up to the higher one. When saturation is reached, that is when the lower level is completely emptied, absorption of the radiation in the dye ceases suddenly, thus rapidly changing the Q of the cavity. Phthalocyanines are commonly used as dyes, the same dyes that are used in inks[7]. Saturable absorbers in glass ($CuSO_4$ RG8-Schott Filter or URANYL in Corning 3-78) can also be used; high power densities tend to damage the shutter.

3. FREQUENCY TUNABILITY

From its very nature the LASER stimulates the emission of the radiation associated with the transition between the higher and lower lying states of the atom, ion or molecule in the resonant cavity. Although one frequency may be the dominant frequency the following processes give rise to some variation in the frequency of the radiation emitted from the LASER, and its associated optical system:

a. Modes of oscillation - As demonstrated in the previous lecture, within the natural spectral band width of the emitted radiation, the physical dimensions of the optical cavity will cause a very large number of standing waves or modes of oscillation to exist in the cavity. Not all of them will be caused to oscillate if for no other reason than the inversion condition is not met for all of them. However, associated with each spectral line there are a limited number of modes through which the laser can be tuned. In the ruby LASER, as in the He-Ne case each of the modal lines may be as narrow as 1 Hz.

b. Stimulated Raman Emission[8] - When for example ruby laser light at 694 nm (6943Å) from a million watt pulsed LASER excites complicated molecules such as nitrobenzene, or in fact any solid, liquid or gas within or even outside of the laser cavity this leads to a number of spectral lines that are shifted down in frequency from the original line amounts corresponding to the electronic, vibrational or rotational levels of the molecules within the material which is being bombarded. This is known as Raman Effect. When the light intensity is very high as in a laser cavity, the energy available as Raman scattered light is many orders of magnitude higher. This is the stimulated Raman effect. For example, if in a focused light experiment the electronic, vibrational or rotational levels of the molecules in the medium are stimulated by the Raman effect, then the refractive index of the material oscillates strongly at one of these frequencies. As more light is added to the system the characteristic frequencies of the molecules are not simply subtracted from the original laser frequency they are added to it as well. These shifted frequencies are called upper and lower side bands, each line of which is a source of light at a different frequency.

The large variety of substances showing the Raman effect provide hundreds of new coherent sources of light from the ultraviolet through to the infrared. As much as 20% efficiency has been obtained in converting laser light to its harmonic frequencies, by means of non-linear processes, such as Raman scattering.

c. Frequency doubling, tripling and quadrupling[9] - Other non-linear processes in certain asymmetric crystals such as calcite, and potassium dihydrogen phosphate (KDP) can lead to the conversion of up to a few percent of the energy contained in a laser beam of frequency ν into frequency 2ν. This is commonly known as frequency doubling, and is one of the primary methods of converting the infrared radiation into visible light. In an analogous way the same type of non-linear process can lead to higher harmonics as well, thus expanding laser radiation out to much higher frequencies, that is into the ultraviolet.

4. SUMMARY OF LASER PROPERTIES

(i) Although in reality an extended source, the LASER is effectively a point source.

(ii) Because the laser cavity can be caused to oscillate in one mode, the source is very monochromatic. In many materials the spectral width of the emitted radiation is more than six orders of magnitude narrower than the Doppler breadth, so that the spectral brightness of the source is unequalled.

(iii) Laser light is spatially coherent, similar to what we would expect from point source at infinity.

(iv) In most gas and liquid LASERS and in some configurations for solid state LASERS, the light that is emitted is highly polarized.

(v) Laser light is highly collimated, with a divergence angle as small as the diffraction limit for the wavelength emitted.

(vi) The brightness of the LASER is unmatched by any other source, particularly when one considers the Q-switched or pulsed high powered LASERS

5. TYPES OF LASERS

In the following short paragraphs I will try to describe the various types of LASERS, indicate the basic science behind their operation, and outline their basic parameters. The first five are solid state LASERS, the ninth a liquid LASER, and the rest gaseous LASERS. In Table 1 I give a summary of the most powerful ones now in use today[10].

a. Ruby LASER[11] - The heart of the solid state ruby laser composition is Al_2O_3 with 0.05% by weight Cr_2O_3 in it. Without the chromium, the crystal is known as sapphire. In Fig.1 we show schematically the physical arrangement of the flash tube and laser crystals. Shown in Fig.3 is the energy level diagram for the chromium ion Cr^{3+} which is the active species in the LASER. This is a 3-level system with two laser lines, but only one, 694.3 nm, dominates because of transition probability for this line is greater than that of the 603 nm line.

In all solid state lasers there is a serious problem associated with the removal of heat from the laser material, since large amounts of energy must be introduced into the system in order to cause the inversion. In the case of ruby where the broad absorption bands of chromium are near 400 nm in the blue, and 550 nm in the green, the high pressure mercury lamp can have as much as ten percent of its light absorbed in this region by the ruby. However, the efficiency of pumping of ruby or any other solid state LASER can be improved with the addition of other ions with suitable absorption bands incorporated in the host latus. These ions then transfer the excitation to the lasing ion, much as happens in the case of the helium-neon laser which will be discussed shortly.

Table 1
High-intensity lasers

Laser Medium	Wave-length	Efficiency (%)	Peak power (W)	Pulse duration	Laboratory
Nd : glass	1.06 µm	0.2	7×10^{11}	1.5 ns	Battelle, Columbus, USA
			4×10^{12}	230 ps	Lawrence Livermore, USA
			10^{12}	1 ns	KMS Fusion Inc. USA
			2×10^{12}	500 ps	Univ. Rochester USA
			5×10^{11}	2 ns	Lebedev, Moscow, USSR
CO_2	10.6 µm	3-5	5×10^{11}	1 ns	Los Alamos, USA
Iodine	1.31 µm	0.5	10^{11}	700 ps	Max-Planck-Inst. Garching, Germany
Hydrogen fluoride	2.7 µm	180 (electrical) 5 (chemical)	10^{11}	35 ns	Los Alamos and Sandia, USA
Dye	605 nm	$<10^{-3}$	3×10^{9}	3 ps	Imperial College London
Xenon	173 nm	>2	4×10^{9}	20 ns	Los Alamos and Maxwell Labs. Inc. USA

The optical quality of the ruby is a critical factor in laser operation. Not only are scattering centres detrimental but so are all variations in optical path from one end to the other. The mode structure, divergence, and the pattern of the radiation generated are largely determined by optical path variations. One of the disturbing observations about the radiation emitted by the ruby rod with parallel

uniform end surfaces is that it does not emit coherent radiation uniformly over the surface. Small, very bright spots - hot spots - appear at the end faces which vary in size and intensity. These reflect the quality of the rod.

It should be noted that although the three-level ruby system is still among the most popular LASERS, it is perhaps one of the most inefficient because the terminal level is the ground state requiring that slightly more than half of the atoms be in an excited state for the system to work. By contrast, most of the solid state LASERS are four-level systems, which normally have efficiencies that are much greater than that for ruby.

b. Neodymium Crystal Lasers[11] - A neodymium LASER is characteristic of all the rare earth ion lasing systems that have now been studied. As in the case of neodymium, all of the rare earth ion systems which include both the spectral ions of R^{2+} and R^{3+} are important, and have been observed imbedded in a number of host crystals and glass. By varying the ion and the host material one can vary the wavelength of the LASER over an extensive range. A partial listing of these is given in reference[5]. The list of rare earth atoms that have been used include all fifteen members of the LANTHANIDE series ranging from La through Lu.

The big advantage of the four-level system (Fig.4) over the three-level system is that energy from a photo flashlamp is absorbed in a very broad fourth level, transferred usually non-radiatively to the third level, followed by a laser transition between the third and second level. The system finally comes to equilibrium again in the ground level. The requirements with regard to inversion are much less stringent than in the three-level system.

The most frequently used host crystals for neodymium include $CaWO_4$, $SrWO_4$, $SrMoO_4$, $Ca(NbO_3)$ and $Y_3Al_5O_{12}$(YAG) with neodymium concentrations of the order of 0.5 to 2%. Of these yttrium aluminum garnet (YAG) operating at room temperature at 1064.8 nm is most commonly used. In other crystals the neodymium lines appear at wavelengths between 900 and 1350 nm. The substitution of the other rare earth ions leads to a multiplicity of other levels in the same general region.

Although the neodymium crystal LASER can be run at room temperature it is much more effectively pumped if the laser rod is at 77°K, since at room temperature the terminal laser level is partially filled, whereas at liquid nitrogen temperature it is not.

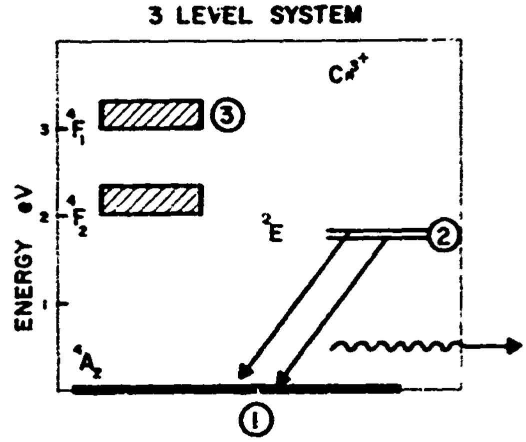

Figure 3. Energy level diagram for the three level ruby system.

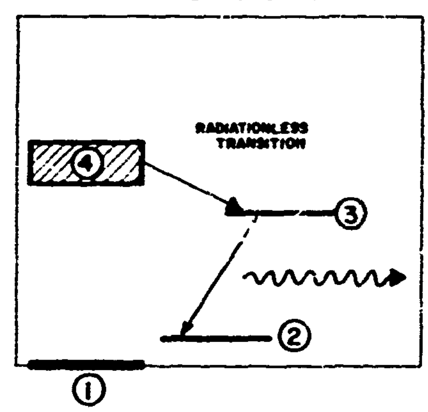

Figure 4. Schematic energy level diagram for the four level system.

c. Neodymium Glass Lasers[11] - The neodymium crystal LASER is a useful tool for the research laboratory however where high power is needed neodymium ions embedded in glass (barium crown glass being the most favorable medium) come close to the potential of the ruby LASER. Neodymium glass laser rods that are two to three m in length and three to four cm in diameter are commonly used. Such LASERS can deliver more than 5000 joules in a single pulse. As with the ruby and crystal LASERS, the glass LASER is excited by means of a xenon flash tube. Furthermore, any of the rare earth ions may be embedded in glass giving laser action over a wide range of wavelengths.

The main advantages of glass as a laser host, are flexibility of size and shape of the rods and the excellent optical quality. There is also a flexibility in some of the physical properties, in particular the refractive index, which may be varied from approximately 1.5 to 2.0 by selection of the glass. It is possible to adjust the temperature coefficient of the index of refraction so as to produce thermally stable optical cavities. However, the major disadvantage of glass is the low thermal conductivity which imposes limitations on continuous operation or high repetition rates.

Although times shorter than 1 nsec can be obtained in the giant pulse laser systems by Q-switching, it is possible by developing oscillations within the giant pulse to produce peak pulses with half-widths of the order of picoseconds. The highest peak power achieved thus far by solid state LASERS are obtained within the giant pulse mode in combination with respective ultra-short pulse techniques. These methods are particularly important for specialized uses such as laser fusion.

d. Semi-Conductor LASERS[11,12] - Of the solid state LASERS the semi-conductor LASERS are the most efficient, and are by far the easiest to modulate, but they operate effectively only at very low temperatures. Unlike most other LASERS where electrical energy is converted first into photons or into electrons that bombard the system, in semi-conductors it is possible to convert electrical energy directly into coherent light. Such conversion takes place in the diode injection LASERS in which excitation is the immediate result of work done by an imposed electric field on the charge carriers in the material.

A schematic energy level diagram for a PN junction diode is shown in Fig.5. Semi-conductor LASERS depend on radiative recombination of electrons and holes of semi-conductors for their operation. Only certain semi-conductors, those such as GaAs with a direct gap between conduction and valance bands are suitable.

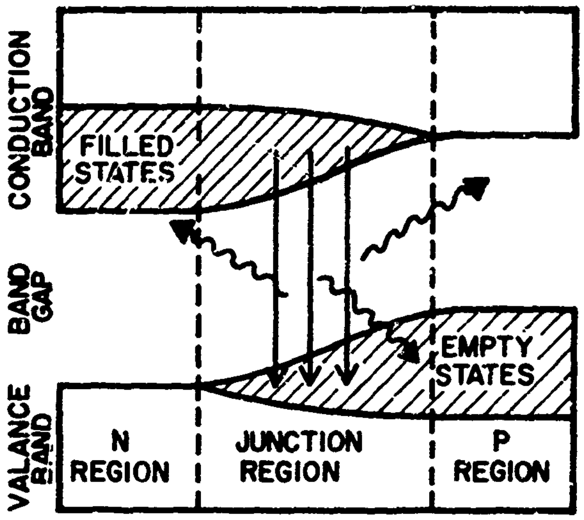

Figure 5. Schematic level diagram for PN junction laser excited with an electric field.

Semi-conductor LASERS differ from other solid state LASERS in most of the physical and geometric characteristics. They are two to three orders of magnitude smaller in size than the typical crystal or gas LASER. The largest dimension of a common semi-conductor LASER is at most 1 mm. The relevant physical properties of semi-conductors and their variations with external parameters such as pressure and temperature thus make them good candidates for tunability of energy.

Gallium arsenide occupies the same role among semi-conductors that ruby occupies among ionic crystals. It is the first and the most used semi-conductor laser material. The band gap in GaAs varies with temperature and in purity content and pressure. At 77°K the band gap of the pure crystal is 1.51eV. At 300°K it is only around 1.41eV. Electron-hole recombination is obtained from heavily doped GaAs diodes (77°K) with a spectral distribution that has a peak between 840 and 850 nm. This corresponds to a photon energy between 1.46 and 1.48eV. Several hundred watts of peak power may be obtained from a GaAs diode in pulsed operation at 77°K whereas only 15 watts has been reported at room temperatures.

The light emitted from the diode is usually plane polarized but the polarization varies from one diode to another. An effective emitting area is maybe as small as 2 µm. As a result, the divergence of the beam is about 10°, much broader than beams radiated from ion crystal lasers. High power diode LASERS not only emit in the near infrared region around 840 nm but also in the blue region 420 nm, twice the frequency of the infrared radiation. The blue emission is the result of harmonic generation or frequency doubling within the diode itself.

A large number of other injection laser systems have been developed with wavelengths which vary through much of the spectral region. Furthermore, one of the advantages of using semi-conductors is that the wavelength can be shifted over a considerable range by alloying. Semi-conductor lasers can also be optically pumped, or pumped by high-energy electron beams, or by electric field breakdown within the system.

e. Organic Dye LASERS[13] - Although the organic chelate LASERS are built with rare earth ions and non-organic niodeodymium-selenium oxychloride LASERS exist, most important of the liquid LASERS is the organic dye LASER. Such LASERS have emerged as the most versatile laser systems now available; both pulsed and continuous operation are possible. With phase or mode locking of the waves within the resonant cavity pulses as short as one picosecond have been obtained. The emission from organic dyes is extremely broadband. Consequently, as a research tool, its use is virtually unlimited, since with the proper choice of organic dyes it is completely tunable over a range that runs from the infrared through to the ultraviolet. In a recent article[14], a list of more than fifty organic dyes which can be used in the dye LASER have been given. Since that time many chemical companies have been active in developing new dyes.

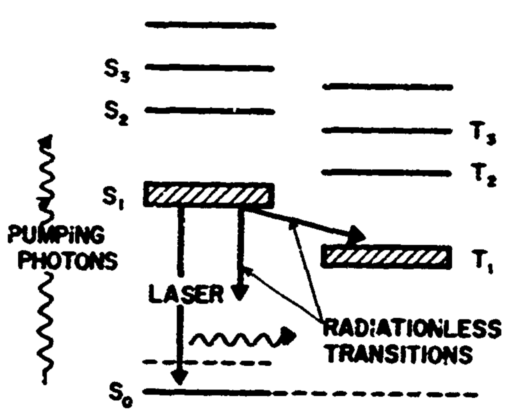

Figure 6. Schematic level diagram for the organic dye LASER.

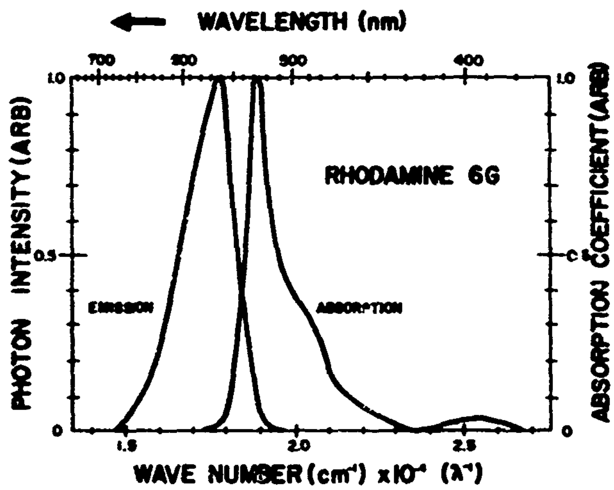

Figure 7. Absorption and emission curves for rhodamine 6G.

The operating principles are the same as any LASER (Fig.6). When optically pumped, dye molecules are raised to the lowest excited singlet state S_1 either directly or via cascades from higher singlet states which relax quickly to S_1. Lasing involves the return to the ground state S_o by stimulated emission of a photon. In practice the process is very complex. The light emission has competition from several other processes, mainly the non-radiative conversion of S_1 to the state S_o and from inter-system crossing to the triplet T manifold. In particular the accumulation of dye molecules in the triplet state T_1 can be detrimental to laser action if these triplet molecules absorb the light from the singlet system,[11] thus diminishing amplification within the cavity. Shown in Fig.7 is the characteristic absorption of one of

the popular dyes, rhodamine 6G, as well as its emission spectrum. If the laser cavity is not tuned to a particular frequency the system will oscillate over a broad band. For example the characteristic colour of the rhodamine 6G emission is in the orange.

Typical dyes are dissolvable in alcohol or water. In order that the efficiency remains high it is necessary that they be cooled. As a result they are either circulated through the optical cavity or fired in a liquid jet stream through the optical cavity. For stability and reproducibility the use of the jet is becoming more popular. Excitation of the organic dyes is accomplished by optical pumping using either solid state LASERS, nitrogen or argon discharge LASERS, or extremely fast flashlamps. Normally the gain achievable by using dye solutions is extremely high.

Initially dye LASERS were found to operate only with very short pulses. However, a careful study of the quenching mechanisms have made it possible for the system to be run cw.

f. Helium-Neon[15] and other Nobel gas LASERS - All of the gaseous Lasers which follow depend upon a variety of atomic and molecular collision processes which include electron impact excitation, electron impact excitation through resonant processes, electron impact deexcitation (superelastic collisions) photo-excitation as in the solid state case, energy transfer from an excited atom or molecule to another, charge transfer between an ion and an atom or molecule leading to excited products, etc. In the helium-neon LASER which is among the most used LASERS available today population inversion results from electron impact excitation of the helium metastable states followed by energy transfer to upper radiative states of the neon atom

$$e + He \rightarrow He^* + e'$$

$$He^* + Ne \rightarrow He + Ne^*$$

$$Ne^* \rightarrow Ne^{**} + h\nu_1,\ h\nu_2 \text{ or } h\nu_3.$$

The schematic energy level diagram is shown in Fig.8. As indicated in the final equation, and as shown in the diagram, the helium-neon LASER operates in three distinct spectral ranges: in the red at 632.8 nm, in the near infrared around 1150 nm and further in the infrared at 3390 nm.

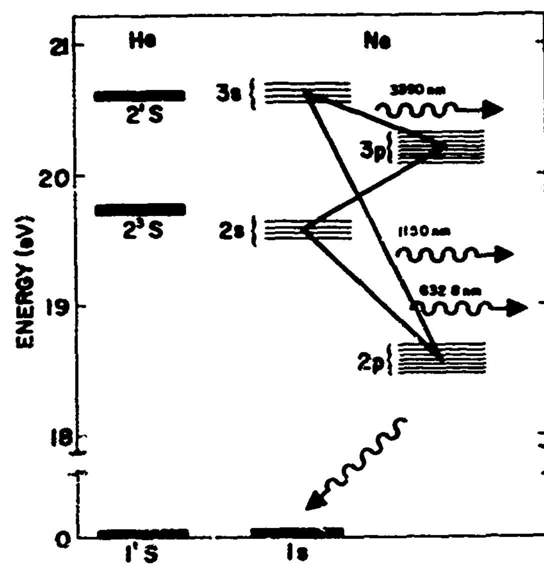

Figure 8. Level diagram for He showing first two metastable states, which transfer energy to the Ne levels which subsequently lase.

He-Ne LASERS were first discovered in 1960 by Javan et al[16]. Although there are three dominant lines, as many as thirty neon transitions can be caused to oscillate, most under very special conditions. As one can see in the diagram, the 632.8 nm transition is in competition with the 3390 infrared transition. In order to cause the system to oscillate primarily in the visible it is necessary to suppress the infrared line. This is done in a number of simple and often very sophisticated ways in the commercial LASERS. Because of its simplicity and significant power in the visible the He-Ne LASER is used primarily for instructional purposes and in the laboratory. Furthermore, it is the primary laser tool used for alignment and is a source of coherent radiation in holography. Its power output ranges from less than a milliwatt to powers well in excess of a kwatt. Under normal circumstances the He-Ne LASER is run in a continuous mode, although it can be operated at higher power in a pulsed configuration.

Although the He-Ne LASER is the principal nobel gas LASER it should be noted that gas discharges in helium, neon, argon, krypton and xenon can produce atomic radiation that can be the basis of a LASER. Not only are the pure gases used, but often it is found that mixtures produce enhancement of some of the laser lines. As a rule the output power of the nobel gas LASER is low. Under normal conditions they work in the cw mode. In all cases the laser configuration is the same as the helium-neon case. It becomes more difficult to achieve stimulated emission at short wavelengths because of the required pumping power increases as the 3rd power of the frequency. The large emission band widths reduce the net gain of a given population inversion. These difficulties are further aggravated by the absence of effective sources capable of rapidly pumping the nobel gas to higher energy levels.

Until recently stimulated emission at shorter wavelengths has been through the excitation of gases by high powered ns pulse discharges. Now high energy-high current electron beam pumping has resulted in some of the shortest laser wavelengths observed to date approaching 110 nm. Recent progress in electron beam pumping of vacuum UV LASERS is an outgrowth of work on condensed nobel gases by Basov and his co-workers[17] at the Lebedev Physical Institute. In this paper the Russian group demonstrated stimulation of 176.0 nm radiation in liquid xenon which resulted from the diatomic molecule of xenon making a transition to its repulsive ground state in a fashion similar to that shown in Fig.9. The final state of the xenon excited dimer came about through a sequence of events such as:

$$e(\text{high energy}) + Xe \rightarrow Xe^+ + 2e$$

$$Xe^+ + 2Xe \rightarrow Xe_2^+ + Xe$$

This occurs in $\sim 10^{-10}$ sec at 10 atm.pressure. Ionization was then followed by three-body recombination

$$Xe_2^+ + Xe + e \rightarrow Xe_2^* + Xe$$

the final transition from the excited xenon dimer to the repulsive ground state represents the laser transition which occurs in a time approximately 10^{-12} sec.

g. Ion Lasers[18] - In principle, ion LASERS are similar to other gas discharge LASERS, however they

operate in the near infrared, the visible, and the near ultraviolet. Ion LASERS operate with considerable dissipation of power but their peak energy output is usually orders of magnitude higher than those of atomic gas LASERS. They are not an efficient LASER, since in the discharge it is necessary to excite a level of an ion, thus requiring considerable amount of energy, most of which ultimately ends up as heat. The output of the LASER is dependent upon the square of the current. The first electron ionizes the atom while the second excites it. Although many ions have been excited through discharges the most popular ion LASER is the 488 nm Ar^+. The argon ion LASER has become very popular, primarily for therapeutic work in ophthalmology. Besides argon ions, neon, krypton, xenon, oxygen, mercury, iodine, iron, chlorine, bromine, boron, carbon, sulphur, silicon, manganese, copper, zinc, germanium, arsenic, cadmium, indium, tin and lead ions have also been used in ion LASERS as the active medium. The cadmium ion LASER is now becoming very popular.

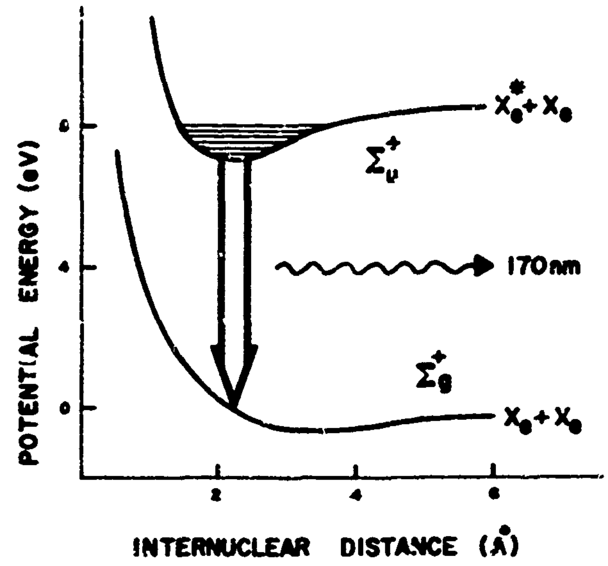

Figure 9. Level diagram for lowest two levels of the high pressure Xe gas laser.

It has been suggested[19] that charge transfer might be an effective method of producing excitation of radiation in the visible and UV. In fact, for cadmium, zinc and tin, this has long been suspected of one of the primary pumping mechanisms. Quite recently it has been demonstrated by a group at the University of Texas[20] that charge transfer of He_2^+ with N_2 leads subsequently to radiation of the nitrogen ion at 427 nm with an efficiency approaching 2%.

h. Molecular Lasers[21] (Not including Chemical Lasers) - The most significant advances in laser technology have come within the last five years in this area. It is probably fair to say that all molecular gases can be made to lase in one mode of operation or another. As pointed out in Lecture 1, within a molecule there are combinations of electronic, vibrational and rotational transitions. Most of the molecular LASERS that have been made operative have involved the vibrational-rotational transitions. However, a substantial number of transitions have been observed in the infrared, the near infrared, visible and ultraviolet, associated with electronic transitions of a number of diatomic and triatomic systems. The most useful electronic transitions thus far used have been in nitrogen, particularly associated with what are known historically as the first positive, and second positive systems. In the first positive system which involves the transition between $B^3\Pi_g$ and $A^3\Sigma^+_u$ electronic states. As much as 500 watt peak power output has now been measured through the wavelength ranges 775 and 758 nm. The transitions associated with the second positive system of $N_2(C^3\Pi_u^+ - B^3\Pi_g)$ lie in the near ultraviolet. More than 30 laser lines of this system have been observed between the various vibrational-rotational branches. Other groups of lines have been observed at 357.6 nm and 33[illegible] nm. Pulse powers in excess of 300 kW are routinely obtained. Other electronic transitions have been observed in the infrared. Besides nitrogen, H_2 and D_2 have been caused to lase associated with an electronic transition.

The most significant work in the past five years has been associated with vibrational and rotational excitation of N_2 and CO_2 as well as mixtures of these gases with He and sometimes minute impurities. All of these systems have been caused to effectively lase with high powered output in the standard gas discharge laser tube. However, the biggest advance has occurred in several areas, particularly associated with the high pressure gas discharge systems[22]. It is only these systems which I will consider, since they are the basis of many of present and future industrial and military uses of LASERS.

The high pressure systems include the TEA LASER (Transverse Excited Atmospheric LASER), the E beam and Blumlein excited LASERS and the electric discharge gas dynamic LASER. Before examining any of the technical details let us consider the basic physics of the processes involved. In N_2 the lowest vibrational level of the molecule in its ground electronic state is excited through the formation of giant N_2^- resonances in the vicinity between 2 and 3 eV. It is the resonance excitation that is primarily responsible for the large probability of forming $N_2(v = 1)$. In mixtures of N_2 and CO_2, CO_2 in the first asymmetric vibrational mode is excited by resonant vibrational energy transfer from the v = 1 level of N_2. This is demonstrated in Fig.10. The CO_2 1060 nm transition then results between the first asymmetric vibrational mode and the symmetric vibrational mode while the terminal level is subsequently destroyed through cascade to the ground vibrational level. The vibrational levels of N_2 are metastable and therefore represent a reservoir of stored energy for selective and effective excitation of CO_2.

A pulsed transverse excited atmospheric LASER in CO_2 was first reported by Beaulieu[23] in 1970. More recently various methods of preionization involving either electrons, heavy particles or ultraviolet radiation are now used in conjunction with the TEA type LASERS to obtain large volumes of gas discharge and thus more energy. Preionization results in large quantities of charged particles in the gas volume prior to the initiation of the discharge. These charges aid in the production of a large volume glow discharge of high spatial uniformity. In a recent embodiment the onset of the electrical discharge is controlled until the optimum degree of ionization exists within the discharge volume. One such CO_2 system developed by Richardson, et al[24] has given output pulse energies at 1060 nm of 300 J in the multi-gigawatt range and with an overall energy extraction efficiency approaching 10%.

The production of stable uniform discharges at high pressure has also been accomplished using electron beam (E-Beam) preionization. This technique involves the use of a high energy (0.1 to 1.5 MeV) electron beam to ionize the gas. An applied electric field accelerates the resulting charges and provides electrical excitation of the laser molec . The discharge is not self-sustaining without the electron beam. In a recently developed system described by Daugherty[25] electron beam control discharge was produced in a 40 litre CO_2-N_2-He gas at 1 atm. The output is ~2kJ and a pulse length ~40μsec.

Increased operating pressure has led to greatly improved performance by increasing pulse energy peak power and maximum permissible repetition rate. At very high pressures much greater than one atmosphere the discrete vibrational rotational lines broaden and merge into a continuous emission band. Such a LASER will now be tunable over a broad spectral range or mode lock to produce picosecond (10^{-12}sec) pulses. Already, as reported by the Russians, CO_2-N_2-He LASERS have been operated at pressures in excess of 50 atm. Cw systems in excess of 25 kwatts have now been developed in high pressure flowing systems[26]. One of the significant advances in the study of the dynamic laser system has been the complete analysis and predictability of the system using the basic cross-section data available[27]. The dependence of power output on the temperature, pressure, gas flow, gas mixture and impurity has been studied thoroughly, has led to a predictable increase in efficiency.

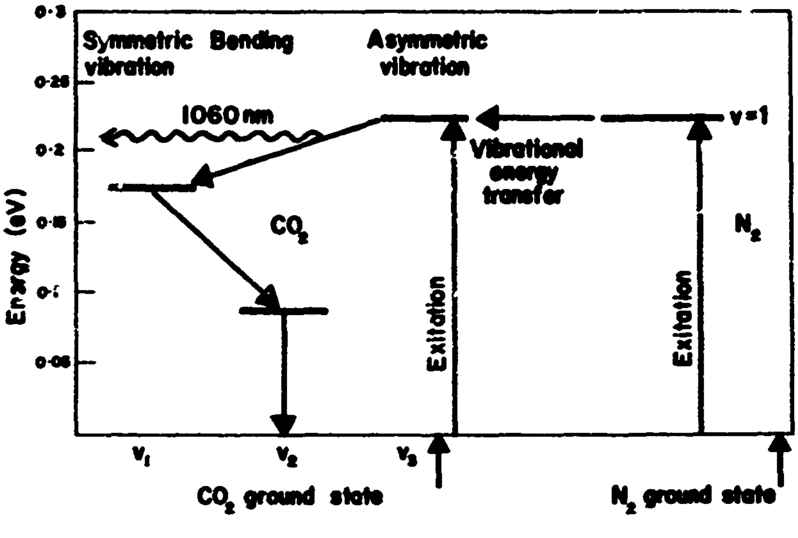

Figure 10. Level diagram for the first vibrational level of N_2 and some low lying vibrational levels of CO_2 which couple to N_2 (v = 1).

The Blumlein pulse generator will not be described here. It is sufficient to recognize that it can produce excitation currents of hundreds of kiloamperes at voltages of about 100 kv with a rise time near 2.5 ns. Because of the enormous power available from this generator LASER action has been observed in many systems in the VUV region.

j. Chemical Lasers[28] - Many exothermic chemical reactions lead to population inversion, primarily of the vibrational and rotational states of the ground electronic state of the diatomic product. This process has been studied by many, in particular J.C. Polanyi and his associates[29] who proposed this mechanism for creating an inversion. Because chemical reaction energies can be very large compared with vibrational energy level spacings a reaction can produce molecules which are excited to very high vibrational levels. In fact a major part of the energy that is liberated in many chemical reactions leads not to kinetic energy of the fragment products but rather to internal excitation.

One of the most important chemical lasers involves the production of excited HF or DF molecules. For example in the H + F_2 reaction about 60% of the reaction energy appears in vibration so that the average vibrational level of the HF molecules produced is v = 6. Because the spacings between the vibrational levels of both the HF and DF molecules vary markedly from one vibrational level to another, a broad range of radiation wavelengths is emitted. In HF it ranges from 2600 to 3600 nm, while in DF 3500 to 4700 nm. In addition each vibrational level has associated with it a large number of rotational sub-levels which lead to a large total number of different laser wavelengths. H_2 and F_2 do not undergo a rapid direct reaction. However in the presence of dissociated hydrogen or fluorine they can react rapidly through the F+H_2 and H+F_2 elementary actions, which together form a chain of reactions leading to excitation. In most chemical LASERS studied thus far, it is necessary that free atoms be involved. These atoms can be formed in an electric discharge leading to cw operation or in a shock tube, or at high pressures in the TEA laser configuration, or in a flash photolysis apparatus where the chain of reactions is initiated by photo-dissociation.

6. APPLICATIONS OF LASER LIGHT[30]

Over twenty-five years ago at the time of the invention of the transistor one could predict essentially what has happened since that time. Because the transistor was an improved device for performing existing functions, its evolution was comparatively straightforward. The LASER on the other hand produces light that is different in both quality and intensity from light generated from any other source. Consequently some of the more obvious uses of LASERS in existing systems, such as conventional interferometry will turn out to be less important than the development of new systems that take advantage of the unique characteristics of laser light. Perhaps the best example of this has been the rapid development of the new field of interferometry known as holography, that is, the storage of three dimensional information in an interferogram. Though not a new idea the potentials of holography were realized only after the invention of the LASER.

Because of the highly specialized properties of the LASER which were discussed at length in comparison with other sources at the end of Lecture 1, properties such as brightness, spectral brightness, monochromaticity, spatial coherence, the fact that laser light effectively comes from a point source make possible applications and developments which today have not even been considered. Any list of applications prepared unquestionably will be out-of-date within a few years. The important point to remember is that laser light has now become an integral part of man's everyday experience, in the home, in the office, in the shopping centres, in manufacturing, communication and power production, in our military arsenal, and primarily in the research laboratory. The brightness of the source and the fact that it can deliver enormous power make it a hazard for man, particularly the most sensitive part of man, his eye. As we consider the various applications, try to keep in mind how in each this hazard exists and can be minimized. In subsequent lectures many aspects of this problem will be discussed.

a. LASERS in Metrology - Laser technology is important in the determination and maintenance of standards. However, the performance of He-Ne LASERS stabilized by saturated absorption in methane at 3390 nm

and iodine at 633 nm is such that they are being considered as frequency standards. These laser systems have shown a frequency stability comparable with the cesium-beam frequency standard now accepted and a reproducibility much better than the krypton-lamp length standard now universally used. Such reference systems are now commercially available. Based upon the accepted frequency and length standards, the velocity of light is now fixed at 299,792,458±4 m/sec. Even allowing for the improvement with LASERS, the value is not expected to change.

b. Communication and Information Storage - LASERS will no doubt have their largest impact on the total human experience through the areas of communications, information storage and retrieval. At optical frequencies the band width is such that all the information presently transmitted through all telephone circuits, all radio, television and radar systems in principle, can be carried on one laser beam, provided the logic were available to code and decode the signals in orderly fashion. Besides the large information content that can be included in a single optical beam, one has the definite advantage that in optical communication systems the normal electromagnetic interference is not a problem. From the point of view of maintaining communications during times when there are natural atmospheric interferences, such as from an electrical storm, or during times when enormous interference is generated from an atomic blast, the optical communication system is not affected.

Information can now be carried directly on laser beams through the atmosphere for short distances. However, dust, temperature, fog, to a large extent, interfere with the continuous use of such systems over long distances. In outer space, the situation is different, and already LASERS are being used for communications between satellites. To eliminate this problem laser light is now being piped through small optical fibres, and in time it is clear that most communication at telephone, radio and television frequencies will be carried in small fibre bundles.

The development of semi-conductor LASERS with active areas small enough to readily match the optical waveguides as part of integrated optical systems now make possible the in-line amplification of the signal in fibre-optic transmission lines. Besides amplification of the signal, the semi-conductor LASER affords a high efficiency method of coupling the signal onto the optical frequency carrier wave.

If the amount of information stored in scientific and technical journals, and in corporate and government files continues to grow at the rate that it is growing today, the weight of the material might well approach that of the earth by the early 21st century. In response to the exponential growth, we have already begun to store information on microfilm and in computers. However, even with these stopgap measures it is clear that we will lose the information storage and retrieval battle unless new techniques are developed. Such techniques are presently under investigation and in limited operation today.

The heart of the storage system is the hologram. The information containing interference pattern is frozen within the photographic emulsion or some special crystals. Crystals such as lithium niobate $LiNbO_3$ have the property that many hundreds of thousands of holographic interference patterns can be stored in one very small single crystal, and can be edited or removed at will. To look at a hologram one sees a hodgepodge of specks, blobs, and whirls, which represent the frozen interference pattern. By transmission of laser light through the hologram, or the reflection of it from the holographic crystal, one can reconstruct the image not only in two dimensions, but in three dimensions. Written material can be stored as a series of holograms in page sequence. One holographic cube can be used to store a million pages of material. The information stored in the holographic library can then be transmitted to universities, companies, even private homes from the central library through light pipes to a television receiver. Not only can information be stored in three dimensions, and in bulk, but it can be stored in multiple colour. In the last few years the application of holographic techniques, coupled with digital computing techniques, and television monitoring, a field now called optical computing, has contributed much to our understanding of the problem of storage and retrieval of data. Furthermore, it has made possible the active and continuing processing of information on a time scale that has never before been imagined.

c. Production and transmission of power - The use of LASERS in power production is coupled intimately with nuclear technology. In the nuclear fission process a large percentage of the cost is associated with a separation of the uranium isotopes. It has now been demonstrated and will soon be the basis of commercial processes that high powered LASERS can be used to excite and subsequently ionize uranium atoms associated with a particular isotope. As one scans the technical literature today on LASERS, a large percentage of it is associated with isotope separation.

For the Canadian reactor, unlike the American system, the uranium that is used is unenriched. Nearly 40% of the total cost of reactor produced power is associated with the production and handling of heavy water, the moderator used in the Canada CANDU reactors. Normally, the heavy isotope of hydrogen, deuterium, represents approximately one part and 10^4 of the hydrogen atoms available in nature. Of the total cost of producing heavy water, 70% is associated with the first factor of 10 enrichment. Once again, LASERS are being used in an attempt to attach those molecules that are deuterium containing, in an attempt to especially separate them from the large bulk of material.

Probably the greatest call for high power laser technology is in the area of laser fusion. In order for fusion to occur, it is necessary that either high powered gas, or glass LASERS, be developed that will deliver terawatts (10^{12} watts) in times approaching picoseconds, that is 10^{-12} seconds. Such giant systems are nearing completion today. High powered, high pressure gas LASERS are now working with efficiencies that approach 50%. It therefore becomes reasonable to imagine that laser systems can be considered for the transmission of power over long distances, and into awkward places. Unfortunately in the infrared, water vapour is a strong absorber, thus making it difficult to transmit power at these frequencies.

d. Lasers in the community - Besides the obvious application of laser technology to communications there are a number of other uses that are now being developed. Automated checkout for the supermarkets promises to be a multi-million dollar market for laser systems. At present the helium-neon LASER has assumed a place alongside the integrated circuit, and the semi-conductor memory as a reliable electronic component in these systems.

Because of their high efficiency and brightness, LASERS are playing an increasingly important role in display systems. Furthermore, the possibility of eventually using injector LASERS for light bulbs is certainly real. For the moment, the LASERS that have been developed do not operate in the blue region of the spectrum. The efficiency of the present light bulb is approximately 10%, and their life is short. A blue diode LASER, such as SiC may be able to operate without being cooled with an efficiency approaching 25%. The coherent monochromatic radiation that would be produced could be converted to heterochromatic light by surrounding the LASER with the proper type of phosphor which would efficiently absorb the laser light, and reemit it over a broad band of frequencies. Such a system would be extremely simple, and long-lived. Before the application of infrared laser light to the cleaning of works of art, such as statues, and national monuments, the process has required many man years of painstaking labour to scrub the dirt from the surface with sand. Now with the aid of the high powered infrared LASER these objects d'art can literally be scrubbed with light. The light is preferentially absorbed by the soiled surface and the preferential heating of the dirt causes it to be boiled from the object. The same principle has been used with the laser eraser which is capable of vaporizing ink from paper without appreciably heating the paper. Museums have now included holographic techniques in their arsenal of weapons used in determining authenticity of works of art.

e. LASERS applied to pure and applied science - Lasers find their greatest application in scientific laboratories. The most obvious application of course is as a tunable light source reaching from the sub-millimeter range in the far infrared through now to the vacuum ultraviolet. The obvious primary use is of the tunable light source in conjunction with the standard spectroscopies. The spectral brightness of many laser sources makes them ideal for studying properties of atoms and molecules which otherwise could not be studied. With the aid of the LASER, investigation of non-linear optical phenomena has grown rapidly. Prior to the advent of the LASER in 1960, the electric field strength associated with commonly occurring intense light sources might be in the vicinity of 1000/m volts/m. With the advent of the LASER, electric field strengths produced by LASERS are now well in excess of teravolts/m (10^{12} volts/m).

In much more modest fields multiphoton processes begin to occur within the material which lead to optical harmonic generation. The crystal potassium dihydrogen phosphate is one of the materials often used for this purpose. Often the efficiency for producing second harmonic frequency generation maybe in excess of 20%, although typical conversions are between 5 and 10%.

As laser light interacts with gases, liquids and transparent solids, it is scattered both elastically or inelastically. Elastic scattering is called Raleigh scattering, while the inelastic scattering of light is called Raman scattering. Inelastically scattered light will contain lines corresponding to energy loss in exciting various rotational, vibrational and electronic states of the medium. If the light is intense enough it will also contain a series of lines corresponding to the addition of vibrational, rotational, electronic energy to the light of the LASER. This then becomes another very powerful tool for studying the internal structure of materials.

Essentially, Brillouin scattering in solids and liquids is the same process as Raman scattering. However replacing the vibrational rotational, electronic excitation is the motion of an acoustic wave within the material. The frequency of these acoustic waves can be added and subtracted from that of the laser light thus giving a rich spectrum reflecting their magnitude within the material.

Within the laboratory LASERS are often used as intense sources of radiation for pulse radiolysis, that is the time study of a system after energy has been rapidly introduced into it. Furthermore, the LASER is an excellent source of radiation for studying the interaction of non-ionizing radiation with living systems. For example in my laboratory, our primary interest is in studying laser radiation damage within the retina. We also use laser light to assist with detailed studies of basic mechanisms in colour vision.

The laser is now important in cellular microscopy. The effects of laser radiation upon the cell have been studied by a number of laboratories. The laser microscope also provides another instrument for microsurgery of tissue cells and orgenelles. Laser radiation has now been used to monitor reactions in living systems involving brain cells, DNA, and RNA molecules. Because of the monochromaticity of the laser light and the small divergence of the beam, experiments can now be carried out down to sizes which approach one-half micron.

f. Industrial applications of LASERS - LASER technology is finding its way into virtually every aspect of industrial processing. The most dramatic application of LASERS of course is in industrial metal welding, drilling and cutting, ceramic machining and drilling, fabrication of high precision resistors, of printed circuitry, manufacturing standards control, package labelling, and so on. Let us consider a few more detailed examples.

This past year some of the underbodies for the Ford Montego and Torino are being welded with a 6 kw beam from a carbon dioxide LASER which was developed in the laboratories of United Aircraft. Similarly these high powered CO_2 systems are being developed for ship welding, thus cutting by ten the amount of time necessary for fabricating ship hulls. As with most laser systems used in industry, the welding system is invariably computer controlled. Laser beam welders are also important in the manufacture of automobile batteries (lead acid batteries) and in heat treating and surface hardening of such important parts as camshafts and valve seats. There appear to be definite advantages in using the LASER for heat treating since the rapid process leads to the minimum amount of part distortion.

As in the case of heavy manufacturing, the LASER is of importance in the chemical industry. As mentioned above, it is now effective in isotope separation of both uranium for fission reactors, potentially for producing heavy water as a moderator in the heavy water cooled reactors. Over the next few years its full potential will no doubt be developed.

g. Applications of LASERS to Medicine - The largest single use of LASERS in medicine is in therapeutic photocoagulation of ocular tissue. Up until the development of LASERS the greatest advancement has been the xenon Arc lamp; however, with LASERS one can now control the power, the spot size upon the retina, the irradiation time with the tunability of colour to match the absorption spectrum of the

material under irradiation.

Photocoagulation has now been extensively used in treating a number of diseases of the macula. For example, the majority of patients treated for serious central retinopathy have shown an improvement in visual acuity within three weeks. However, diabetic retinopathy is rapidly becoming a chief cause of blindness. It is now estimated that approximately 19% of the blindness in the U.S.A. is caused by such retinal changes. Coagulation of the retina is one of the major approaches to the control of this disease. Although the ruby LASER, which emits at 694 nm in the red, has been used, it has not been particularly successful. Instead, either the argon ion LASER which emits at 488 and 514 nm or the frequency-doubled neodymium doped YAG crystal which emits at 530 nm have more successfully been used. The relatively high absorption of the green wavelength by reduced or oxygenated hemoglobin makes these latter two lasers very attractive in the treatment of retinal vascular anomolies. Treatment of glaucoma, by poking a small hole in the iris with the LASER, has thus far been carried out in Russian laboratories.

In recent years, the LASER has become a surgical tool. Both the infrared CO_2 (10,600 nm) and a green argon ion LASER (488 and 514 nm) have been effectively used as these radiations interact quite dramatically with tissue. The red ruby and He-Ne light are not appreciably absorbed by tissue, blood or water and consequently are of little use. The advantage of laser surgery is seen in the bloodless cut since vessels scar immediately. Attempts now are being made to use laser surgery in awkward places such as in the skull for the removal of cysts.

Because of the high power density and the monochromaticity which sets the defraction limit of the spot's size, the LASER is an excellent tool for microsurgery. Once again the choice of the critical wavelength is important since one is able to irradiate part of the subsystem of the cell with that frequency of light which is best absorbed by it.

The LASER is also being considered as a tool in dentistry. Thus far it has not readily been accepted but in the future it may be important in the treatment of special diseases and for mechanical construction in awkward places.

LASERS have also found extensive use in dermatology, particularly in those areas involving cosmetic changes such as the removal of tatoos, birthmarks, and growths. The early enthusiasm that developed around laser surgery associated with cancers has now lessened because it has been observed in many instances that treatment by the LASER has caused the diminishing of the original cancerous growth but has also caused it to spread to other areas.

h. Mining and Geological Applications of Lasers - One of the most common uses of LASERS now is in surveying. However, the monochromatic properties and its high spatial coherence have made it a superb tool for interferometric measurements of small earth crust movements. Extensive study has gone into the distortion of the earth's crust with the motions of tides and of earthquakes, and with the aid of the LASER, scientists throughout the world are now able to make predicitions as to when and where major earthquakes will occur.

The extreme power of the YAG, CO_2 gas LASER and some chemical LASERS make them excellent candidates for drilling and mining. Already LASERS are in the field in these areas.

LASER light was bounced from the moon. As a result, scientists have been able to determine very accurately the shape of the earth.

Laser radar or LIDAR is now playing a very important role in determining and monitoring pollutants in the lower atmosphere and the LASER is now playing a particularly important role in map-making.

j. Military applications of LASERS - Virtually every laser application thus far discussed finds a use within the military. Conversely, the hundreds of millions of dollars spent on laser-related research and development supported by military establishments not only finds application there, but has quickly found its way back into the community.

Information storage, processing and communications are of primary importance to the military. Integrated optic systems, which allow for coupling of the computers through optical fibres without electromagnetic interference are now commonly used in military systems. The use of holographic storage of information and the holographic techniques in map-making are now under consideration. The use of optical communicators between aircraft and between line posts are now under design. Some are presently in the field, as are laser range-finders and guidance systems.

The power associated with modern LASERS is sufficient for anti-personal weaponry. However, the main thrust will be in developing LASERS that can be used to ignite thermonuclear devices, and to detonate such devices in MERV war heads.

Although not strictly a military application, one of the "far-out" applications for the future will be the use of LASERS for space ship launching and propulsion in space. Such schemes are presently under study at NASA and have been proposed by such leading experts as Dr. Arthur Kantrowitz, Chairman of AVCO Research Laboratory. The magnitude of the LASERS necessary for such a scheme is mind-boggling; however Dr. Edward Teller, his teacher, was asked to comment upon the Kantrowitz proposal predicted: "It will happen before laser fusion will make a contribution in a practical sense. I am interested in... how soon the fusion energy we want to squeeze out of these microexplosions will really give economic power. And I believe propulsion of manned satellites will occur before that occurs."

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INSTRUMENTATION AND MEASUREMENT OF LASER RADIATION

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SUMMARY

In the past decade, many new laser instruments and measurement techniques have evolved. The measurements of primary interest in the evaluation of laser hazards are: output energy or power, pulse duration, beam profile and divergence, and pulse repetition frequency (PRF). The most useful types of detectors and beam profile methods will be discussed. Short-cut check tests will also be given.

1. INTRODUCTION. In any discussion on the measurement of laser radiation for the purpose of evaluating health hazards, I feel it important to explain first the necessity of measurement. Industrial and environmental health specialists and health physicists rely heavily upon measurement in their analysis of environmental hazards. It is not surprising, then, that one of the first questions asked upon encountering a potential laser hazard is: How do I measure laser radiation, and what instrument do I use? A decade ago I asked this question. I was soon to learn that the subject was very complex. Unlike many hazards we encounter, a laser beam is almost always hazardous and indeed, its hazard far exceeds a marginal condition. The output irradiance of most military lasers exceeds exposure limits by orders of magnitude -- typically a factor of 10,000 or even a million times. One then realizes that the correct question may then be: Why should I measure this laser beam? Clearly, no one should place his eye, or even in some instances his skin, into that beam. Well perhaps we should measure reflections. I was soon to learn that trying to measure reflections was very frustrating. The slightest change of a reflecting surface, the insertion of a different surface into the beam, a mode change in the laser beam, or any of a myriad of other changes in the environment greatly affected my measurements. It soon became clear to me that routine measurements to monitor either an area or an individual by instrumentation was a hopeless task. It was necessary to develop an approach of analyzing the potential hazards of a laser based upon the laser's output parameters. The laser beam's hazard can be compared closest, I think, to an exposed high-voltage conductor -- a highly localized hazard. Unless you touch the conductor nothing happens. The beam is unlike an area hazard presented by a contaminated atmosphere, unless a hazardous diffuse reflection or associated hazard exists. We now conclude that any measurements of laser radiation must reflect the need for determining all potential future exposure conditions. Our standards in the USA now require measurements only of the laser output as a general rule for the purpose of determining the laser classifications. In the military environment it is often necessary to measure beam characteristics downrange. Routine monitoring is seldom considered necessary, and measurements are performed at one time by or for the laser developer.

2. LASER PARAMETERS TO MEASURE.

a. One can calculate the irradiance (E) in watts-per-unit-area or radiant exposure (H) in joules-per-unit-area at any distance from a laser. To do this the output power (Φ) or energy (Q), the initial beam diameter (a) and beam divergence (ϕ) must be determined. The relation is:

$$E = \frac{\Phi e^{-\mu r}}{\pi\left(\frac{a + r\phi}{2}\right)^2} = \frac{1.27\ \Phi e^{-\mu r}}{(a + r\phi)^2}$$

$$H = \frac{Q e^{-\mu r}}{\pi\left(\frac{a + r\phi}{2}\right)^2} = \frac{1.27\ Q e^{-\mu r}}{(a + r\phi)^2}$$

Where r is the distance from the laser. (1)

One can use a calorimeter or other types of energy or power meters to measure the output energy or power. The measurement of output beam diameter or divergence can be more difficult. The procedure my associates and I prefer is the use of calibrated apertures with the aforementioned meter. Figure 1 shows the profile of a perfect Gaussian beam profile which is characteristic of a single-mode laser. Figure 2 shows the relative power entering an aperture relative to the beam diameter. We specify the beam diameter at 1/e of peak-irradiance-points, since the total beam power Φ divided by the area of a circular beam defined at these points results in the irradiance of the beam at the peak of the profile in Figure 1. It is conventional for many laser manufacturers to specify the beam diameter at $1/e^2$ of peak-irradiance points. Using this latter definition one would calculate only the average beam irradiance, which is insufficient for safety purposes. Beam divergence is simply the ratio of the change in diameter D of the laser beam with the change in distance r from the laser. If we measure the beam diamter at two locations by using our aperture technique we have measured the divergence.

b. Regrettably the beam profile is not always single-mode. This is particularly a problem with ruby lasers. Figure 3 shows several profiles of an emergent beam from a ruby laser. Measuring beam diameter and divergence of this laser can be quite a problem. With the single-mode laser, one can calculate beam irradiance, or how much laser power is entering a 7-mm pupil or a 1-mm aperture based on two or three measurements. Since the ruby laser profile changes rapidly there is no such simplified method to perform calculations based upon some "effective" beam diameter.

Use of trademarked names does not imply endorsement by the US Army

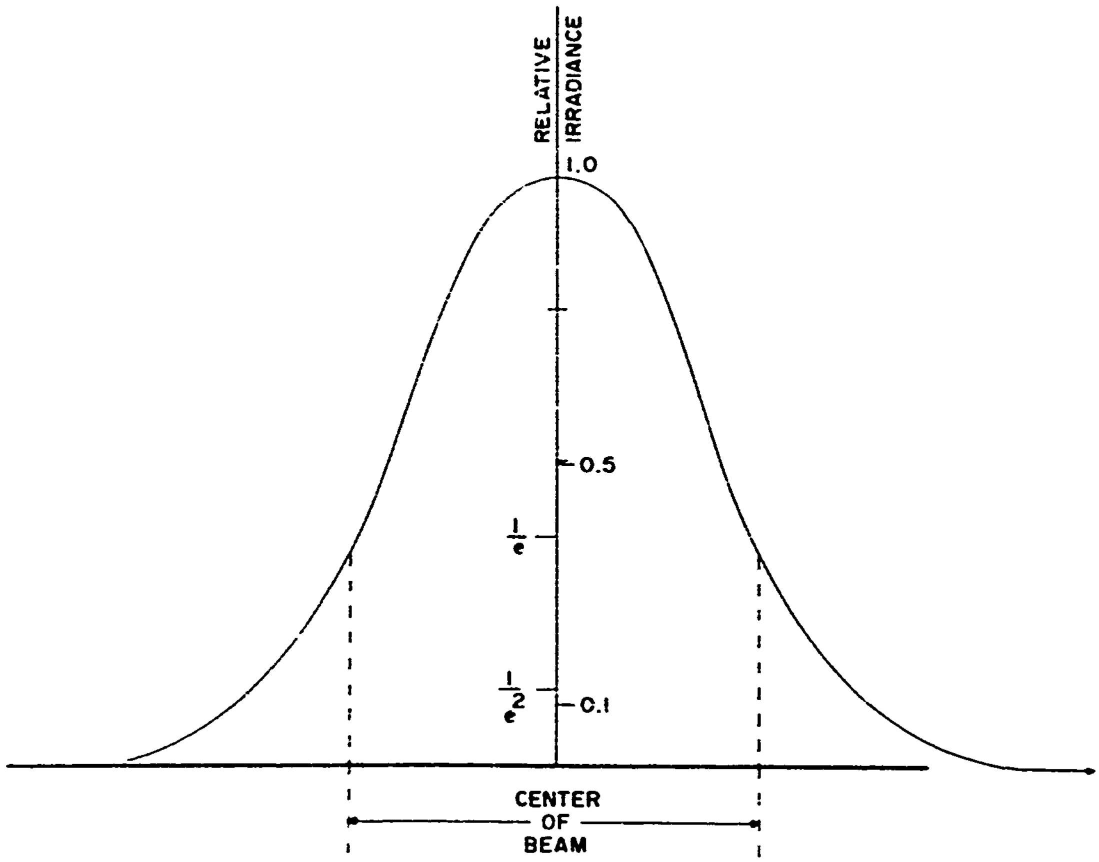


Figure 1. Irradiance Profile of a Single-Mode, Gaussian Laser Beam

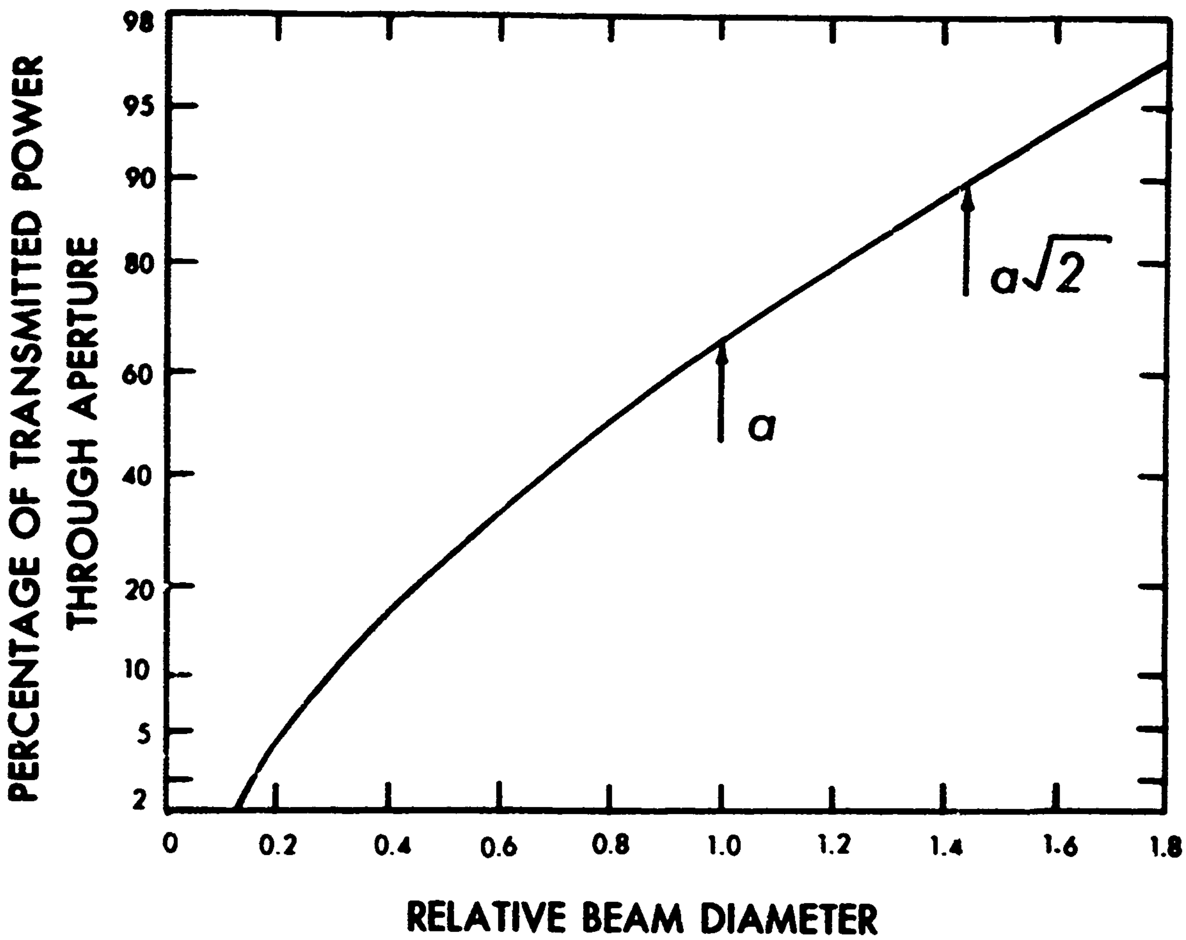


Figure 2. Percentage of the Total Laser Beam Power Which Passes Through a Circular Aperture; Gaussian Beam.

c. From the standpoint of hazard analysis it is necessary to know the maximal output radiant exposure of a pulsed laser to determine if a diffuse reflection hazard exists. The most effective technique we have devised for this purpose is the use of thermally or photochemically reacting surfaces, or photography. In other cases where the beam irradiance is insufficient to cause a surface change in the special beam-profile paper, then a radiometric instrument must be used which has a sufficiently small aperture. Downrange the atmosphere has perturbed the beam profile considerably as shown in Figure 4. Measurements at this distance with an instrument having an aperture of 7-mm (related to the eye's pupil) or 1-mm in diameter are then required. Now that we have discussed the relevant measurements, we can consider the instrumentation that is available.

3. TYPES OF RADIOMETRIC INSTRUMENTS. Radiometric instruments of interest to this discussion generally consist of a detector which produces a voltage, a current, a resistance change, or a charge which is measured by a sensitive electronic meter. We will not worry about the readout meter of the instrument since that seldom determines the selection of the instrument. I prefer taut-band meters because they indicate fluctuations in the radiometric quantity. Others prefer digital meters. But I will caution you: most digital readouts are difficult to read in daylight illumination. The detector is the primary determining factor in selecting an instrument. Each type of detector, be it a quantum detector (photovoltaic, photoconductive, or photoemissive) or a thermal device, has certain characteristics which may be an advantage or a disadvantage for measuring a certain level of optical radiation in a certain wavelength range. No one type of detector can serve for measuring all types of laser radiation. A very sensitive detector can be destroyed by a high power laser beam. A detector sensitive to visible light may not respond to infrared, which is a disadvantage if you wish to measure an infrared laser, but an advantage if you wish to measure a visible laser and do not wish the detector to respond to extraneous thermal sources. Table 1 provides the approximate ranges of irradiance and other radiometric parameters of interest to us for serveral wavelength ranges.

a. Thermal Detectors.

(1) Thermopiles and disc calorimeters, are characterized by a relatively flat response relative to wavelength. The spectral response is dictated by the black absorber, such as gold black, parson's black, or Nextal ®, which normally coats a metal surface. The temperature rise in the metal is then converted into an electrical voltage or current by one of several effects. Because of the thermal mass of this metal, the time required to heat or cool the target, limits the response time of the instrument. In recent years response times have been shortened by using thin-film techniques. Instead of a copper disc or other large metal surface which is useful for measuring radiant powers of the order of 1 mW to 100 W, a thin film of metal which has been vacuum deposited on a nonconducting substrate is used to form a thermopile. Lower powers must be measured, typically 0.01 to 100 mW, but the response time can be less than a second instead of seconds.

(2) Response times of calorimeters and thermopiles may still be too great when one must measure a short-pulse laser. Recently a class of detectors which exploit the pyroelectric effect have been introduced. Rather than responding to a final temperature elevation in a metal, pyroelectric detectors actually measure the rate of temperature change in a crystalline material. Response times of the order of nanoseconds are currently achieved in commercially available detectors. A CW pyroelectric detector is achieved by chopping the input beam so that the temperature rise in the crystal is always changing. A word of caution is appropriate with these CW pyroelectric power meters: Do not try to measure the average power or irradiance of a repetitively pulsed laser, since the laser pulses may or may not pass through the chopper and since the detector is only calibrated with a CW source.

(3) Thermal detectors find their greatest application in measurement of lasers which operate in the infrared region, where other detectors do not respond, or where other types require cryogenic cooling. For a single instrument to measure laser power between 10 mW and 100 W, disc calorimeters are considered very good for all optical wavelengths. Through the use of appropriate entrance apertures, the meter can be calibrated to measure irradiance. In many instances radiant energy output of a pulsed laser can be measured using a disc calorimeter if the beam radiant exposure is below the damage threshold of the absorbing black which may typically be of the order of $1\ J{\cdot}cm^{-2}$ or less. For higher energy pulsed lasers, a ballistic thermopile has often been useful. The disc calorimeter and the ballistic thermopile are both more suitable for the laboratory than for the field, since several seconds or even minutes are required for the detector to cool between measurements of a pulsed laser or for stabilization in a CW measurement. Additionally one is always plagued by a changing ambient temperature resulting from drafts in the measuring environment.

b. Quantum Detectors. These detectors are by far the most sensitive detectors of optical radiation in the 200 nm - 1,100 nm spectral region. The spectral sensitivity of photoemissive detectors depends upon the photocathode material used in vacuum photodiodes or photomultiplier tubes or in the intrinsic characteristics of silicon as shown in Figure 5. Silicon is employed, in solid-state photodiodes, which may operate as either photoconductive or photovoltaic detectors. The type of detector chosen normally depends on what wavelengths you wish to measure and what wavelengths you wish to exclude. Response times of the order of a nanosecond are possible with quantum detectors. The one instrument that my associates and I have found the most useful for hazard analysis of all types of ultraviolet, visible and near infrared lasers utilizes a bi-planar vacuum photodiode detector. With the appropriate selection of input optics and apertures it is possible to measure radiance, integrated radiance, radiant exposuree, radiant power or energy, and irradiance. The disadvantage of this type of instrument is that it can become quite expensive — of the order of $5,000 or more — to have all these features, with sufficient sensitivity. Because of the strong spectral dependence, these instruments are normally not direct reading and the meter reading must be multiplied by one or several calibration factors. Because the 0.4 μm - 1.4 μm spectral region is the retinal hazard region, the levels of radiation required to be measured can be quite small, and the problems of filtering out ambient light and near-infrared radiation can be severe. The use of filters with these types of detectors normally presents great difficulties in the field, since narrow-band filters have a strong dependence of transmission varying with the angle of incidence of laser radiation.

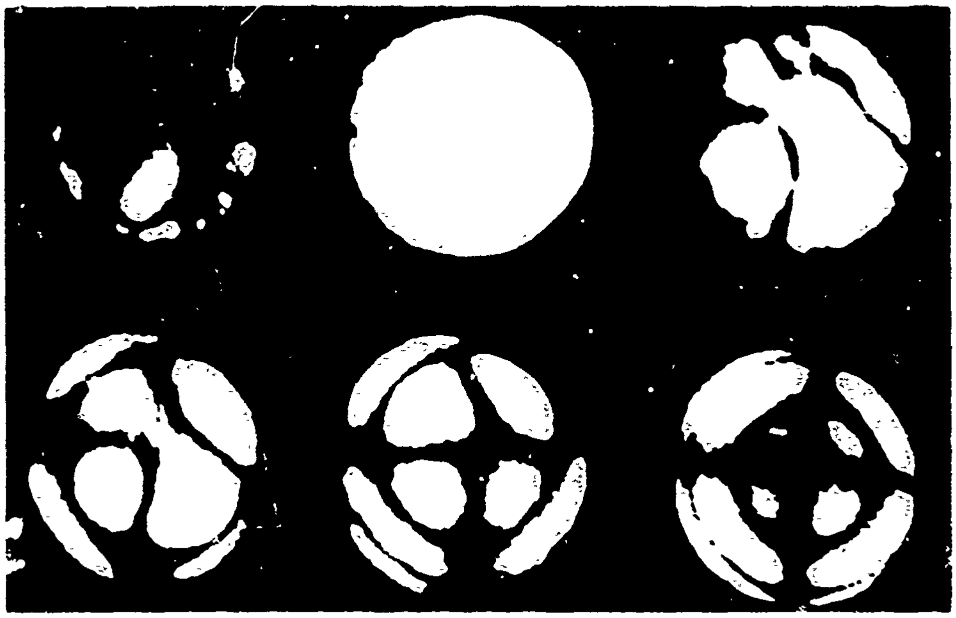


Figure 3. Emergent Beam Profiles for a Pulsed Ruby Laser. Top-Central Pattern is the closest to single-mode operation.

TABLE I

APPROXIMATE RADIOMETRIC RANGES OF INTEREST FOR HAZARD ANALYSIS

Spectral Region (CIE Band Designation)	Irradiance ($W \cdot cm^{-2}$)	Radiant Exposure ($J \cdot cm^{-2}$)	Radiance ($W \cdot cm^{-2} \cdot sr^{-1}$)	Integrated Radiance ($J \cdot cm^{-2} \cdot sr^{-1}$)
Actinic Ultraviolet, UV-B & UV-C, 200 nm - 315 nm	10^{-7} to 10^{-2}	10^{-4} to 10^{-1}	N/A	N/A
Near Ultraviolet, UV-A 320 - 390 nm	10^{-4} to 10	10^{-3} to 10	N/A	N/A
Visible 400 nm - 760 nm	10^{-7} to 10^{-2}	10^{-7} to 10^{-2}	10^{-1} to 10^{3}	10^{-3} to 10
Metavisible or Near Infrared, IR - A 760 - 1400 nm	10^{-6} to 10^{-1}	10^{-6} to 10^{-2}	10^{-1} to 10^{3}	10^{-3} to 10^{2}
Far-Infrared, IR-B & IR-C 1400 nm - 1 mm	0.01 to 1.0	0.001 to 10	N/A	N/A

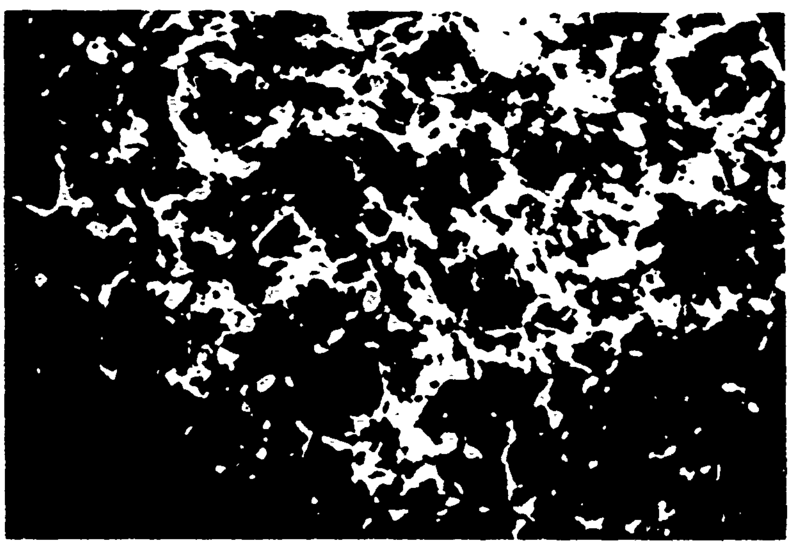


Figure 4. Profile of a q-switched Ruby Laser Beam at a Range of 1 km from the Laser. Only Part of the Beam is Shown to Illustrate Turbulence Effect.

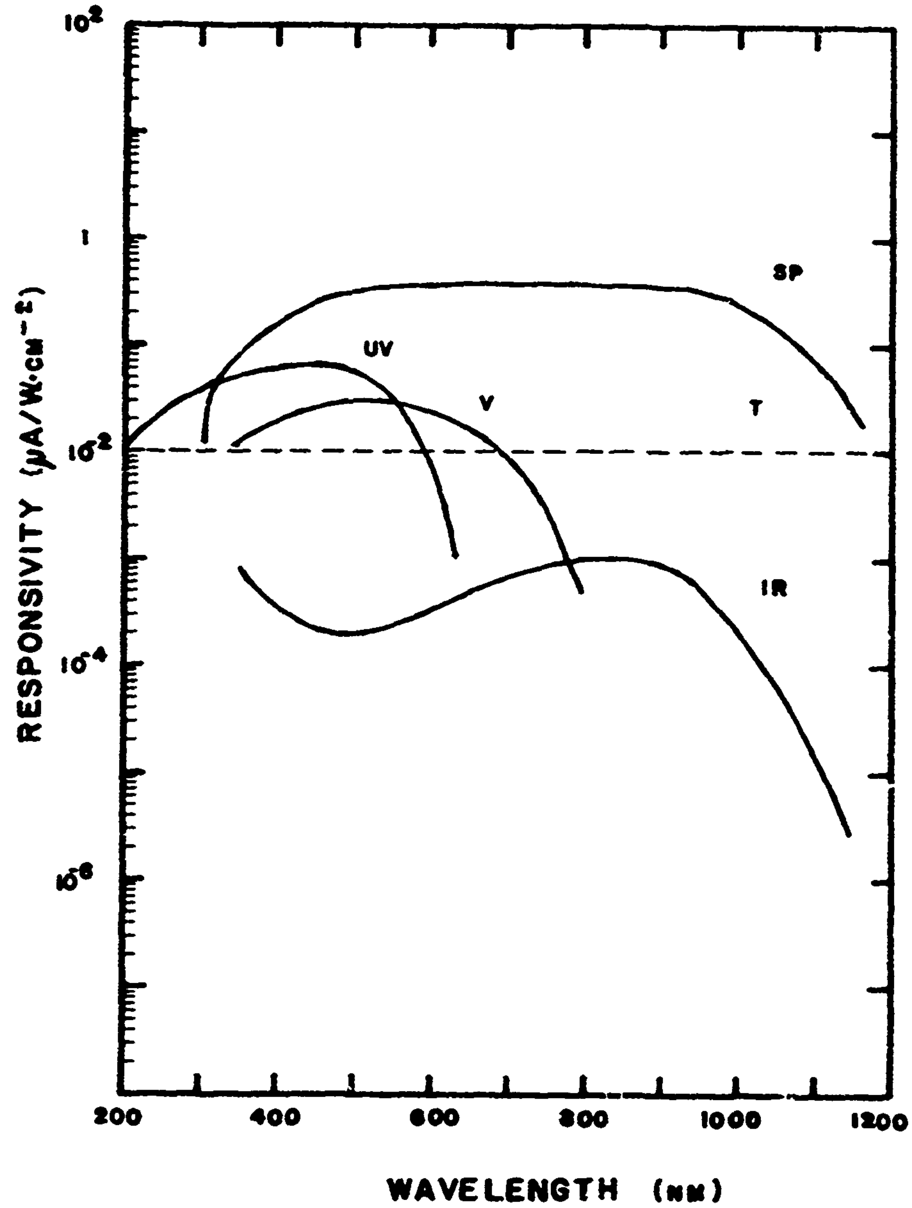


Figure 5. Responsivities for Various Detector Types. SP: Schottky photodiode; IR: S-1 photocathode (Ag-O-Cs); V: S-20 photocathode (Na-K-Cs-Sb); UV: S-5 photocathode (Cs-Sb); T: thermopile. The curves shown are for bi-planar vacuum photodiode detectors, thermopiles and photodiodes used in standard field survey equipment in use at the US Army Environmental Hygiene Agency.

Besides spectral filtering, geometrical filtering, such as the use of a detector hood, may be used to reduce errors introduced by ambient light. In the final analysis, no technique is as effective as performing the measurements at night. This is what we normally do.

c. Hazard Evaluation Meter.

(1) At present no radiometric instruments are available which have been designed specifically for hazard analysis of a wide range of lasers. Indeed, it is unlikely that such instruments will be made in the future because of the great variation in exposure criteria for different wavelengths and different exposure times. Of course, such instruments could be made for each of the specific categories of lasers, but at present a set of these instruments would be quite expensive. In our experience a comprehensive set of radiometric equipment for hazard analysis put together from present commercially available items would cost in excess of $20,000.

(2) Considering the present cost of equipment, one is forced to reconsider the necessity for hazard evaluation measurements and look for alternative techniques. Fortunately, we have found that most high-intensity light sources and modern lasers have fairly consistent maximum output parameters. Because of this consistency of output and the uncertainties in present exposure criteria, there is seldom a need for periodic monitoring of a source. Quite often a source can be determined to have a radiant output either far exceeding or greatly below the present exposure standards. Sensitive illuminance meters may be used to measure permissible exposure levels for CW lasers operating in the visible spectrum. For example, 10^{-6} W/cm^2 at the helium-neon laser wavelength of 632.8 nm is 0.17 ft·cd, 10^{-5} W/cm^2 is 1.7 ft·cd, and 10^{-3} W/cm^2 is 170 ft·cd. However, one must be sure that the illuminance meter is calibrated at that wavelength and that the laser beam completely fills the detector aperture.

4. PHOTOGRAPHIC TECHNIQUES

a. To this point we have considered only radiometric instruments; however, photographic radiometry can play a valuable role in some instances. Determination of the effective source size is of critical importance in making a hazard evaluation of a high-intensity extended light source. The radiance is of principal interest in such an evaluation, and photographic techniques may be used to determine the radiance distribution of a source. It is important to determine the source size which the eye sees for two reasons: To calculate the radiance and to calculate the retinal image size.

b. The effective source size can be accurately determined by photographic methods. Generally, some magnification of the source is required. For small infrared laser diode arrays, a 35-mm camera with a close-up lens and infrared film is quite useful at short distances from the source. At greater distances a telephoto lens is often employed. If the source is sufficiently intense, a high-resolution telescope with 35-mm camera or Polariod back can yield excellent photographs. Unfortunately, rapid-processing infrared film is no longer made. Is should be noted that photographs should be taken at a number of distances as the optical collimator generally used in a laser diode system can change the appearance of the source at different viewing distances (see Figure 6 for a series of photographs taken at different ranges of a laser diode system).

c. One of the most important criteria for evaluating the potential hazards from pulsed laser systems is the output radiant exposure. If the output is above the levels considered safe for viewing diffuse reflections, considerably more stringent controls must be instituted. A rough guideline for determining whether the output is at or above these threshold levels can be arrived at through the use of appropriate heat-sensitive papers or emulsions. If the beam reacts thermally with such paper, there is a possibility of hazardous diffuse reflections. If the beam does not thermally react with a specially chosen paper, it can generally be assumed that the beam does not produce hazardous diffuse reflections. Such papers can also indicate emergent beam profiles for high-energy lasers. Heat-sensitive papers and their thresholds are given in Table II.

d. Another possible photographic-radiometric technique employs photographic emulsions for radiometric measurements of radiant exposure. Absolute photographic measurements of beam profiles are quite complex and, in most cases, unfeasible. Gamma curves (optical density of film versus the logarithm of the radiant exposure) given by film manufacturers should be regarded as only representative of the type of emulsions and sensitizing from which the characteristic curves were derived. If absolute photometric work is attempted, the following criteria must be met:

(1) The response of each emulsion batch of a photographic material must be calibrated at the appropriate wavelengths under processing conditions which are identical to the actual measurement condition.

(2) In addition, there is the problem of making optical density measurements of the developed emulsion. Care must be taken with microdensitometers that read specular or semispecular density. These microdensitometers have a collection angle of less than 180° and in general read somewhat higher than diffuse microdensitometers. This is due to the scattering by the emulsion. The smaller the grain, the more closely the specular density approaches the diffuse density.

(3) The maximum density of most common emulsions varies between 2 and 3, and the dynamic range of exposure between the base density and maximum density is only one to three orders of magnitude. Because of this limited dynamic range, a special-purpose film with three emulsions of differing sensitivities has been manufactured. This special-purpose film is developed in separate stages as is color film.

e. Calibration.

(1) Calibration of all radiometric systems is required periodically. The preferred calibration method for the irradiance levels of interest (Table 1) utilizes a standard lamp. Standard 500-W and

1000-W quartz-iodide tungsten-filament lamps are available from several manufacturers with spectral irradiance and total irradiance calibration with an absolute accuracy of 2 to 10 percent. In our laboratory we use such a lamp to directly calibrate a standard disc calorimeter and a spectral irradiometer. We then place the monochromator between the lamp and the thermopile and use the disc calorimeter to measure the irradiance at a given wavelength of interest which must be known to calibrate the irradiometers which do not have a spectrally flat response. For laser wavelengths we can use a laser calibration source. Some disc calorimeters now have a built in-electrical heater for the copper disc and a known electrical power to this heater circuit results in the same temperature rise in the disc as from a radiant power. This is termed "direct electrical calibration".

(2) The calibration of radiant exposure meters is more complicated unless the instrument behaves linearly with changes in exposure duration. If it does, the irradiance standard and a calibrated shutter may be adequate. There is a great deal of uncertainty in performing measurements of ultrashort pulsed sources, as from Q-switched or mode-locked lasers. Several methods have been developed for measurement of radiant energy output of pulsed lasers. A radiant exposure instrument designed to measure microjoulas/cm^2 or less can be calibrated against such a radiant energy meter by measuring the output energy of a pulsed laser by two methods. The laser output energy, Q, may be measured directly with a ballistic thermopile or calorimeter and indirectly with the radiant exposure meter by measuring the irradiance reflected from a standard diffuse surface such as $MgCO_3$ or MgO_2 and finding H from Lambert's law relating the reflected radiant exposure (H), and the reflectance, ρ, to the distance, r, between the detector and the diffuse surface:

$$H = \frac{Q\rho \cos \theta}{\pi r^2} \tag{16}$$

for r >> laser beam diameter, where θ is the angle shown in Figure 7.

5. MEASUREMENT TECHNIQUES

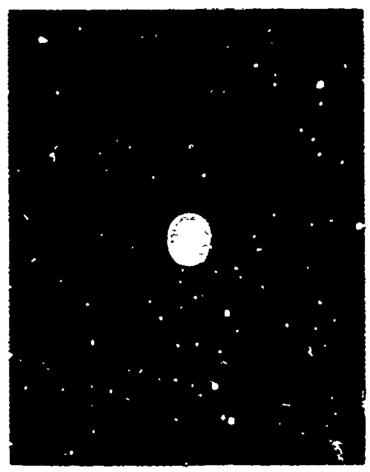
a The many techniques used in photometry and radiometry are far too numerous and complex to detail here: however, some common pitfalls deserve mention.

b. It never ceases to amaze me how often I encounter two different measured outputs of the same lasers obtained by two different laboratories. The answer is almost always a problem of "geometry" or the incorrect accounting for pump light or ambient light. Measurement of divergence at two points a few meters away from the laser will often permit reduction of the error due to pump light and scattered laser radiation from the cavity as well as light in higher order modes. The use of narrow-band filters requires enormous care, and measurement in a dark room or outdoors at night is far more accurate than using filters. Remember that measurements made in the infrared often require careful baffling and that these baffles can heat up and emit significant infrared radiation.

6. CONCLUSIONS. Radiometric techniques and instrumentation are available to analyze hazards of exposure of the skin and eyes to high-intensity optical radiation sources. However, the cost for such equipment remains relatively high when compared to survey equipment available to evaluate many other environmental hazards. Radiometric formulas and manufacturer's specifications, when carefully applied, can often be an adequate substitute for measurements. If detailed information is necessary, however, at least some measurements are generally required. I have endeavored to summarize the characteristics presently available in commercial readiometric equipment, but the audience must remember that radiometric measurement techniques can be quite involved and a knowledge of the effect of source geometry, filter, and detector characteristics is required, as well as good instruments to properly perform accurate measurements.

1 cm

10 cm



100 cm

Figure 6. Intrabeam Photographs of a Gallium-Aluminum-Arsenide Laser Diode Source with Projection Optics. Note that the entire aperture of the projecting optics is "flashed" at 100 cm.

TABLE II
Radiant Exposures Required To Produce a Visible Change on Various Sensitive Media

Sensitive Surface	Q-Switched Ruby Laser (694.3 nm) Threshold (j/cm²)	Q-Switched Ruby Laser (694.3 nm) Saturation (j/cm²)	Q-Switched Neodymium Laser (1.06 μ) Threshold (j/cm²)	Q-Switched Neodymium Laser (1.06 μ) Saturation (j/cm²)
Fully developed Polaroid print, black (coated or uncoated)	0.056	0.095	0.07	0.2
Kodachrome II transparency, black (unexposed)[a,b]	0.17	0.21	—	—
Fully developed, fully exposed photographic film (Kodak Panatomic X)[b]	0.08	0.2	0.08	0.18
Dupont Lino-Write 7 direct writing photorecording paper[c]	0.01	0.05	0.02	0.09
Kodak Linagraph direct print paper[c]	0.01	0.05	0.02	0.09
Black paper used to protect sheet film[a]	0.22	0.22	—	—
Black masking tape	0.07	0.03	0.1	0.12
Carbon paper (Tru Rite type I) Grade A, black medium finish[d]	0.024	0.036	0.04	0.06
Black printer's ink on white paper	0.16	0.25		

[a]Both the color transparency and the black paper used to protect photographic film employ dyes which have greatly reduced absorption characteristics in the near-infrared spectrum. The experimental arrangement used at USAEHA did not permit accurate measurement of radiant exposures above 0.7 j/cm²; hence, threshold data at 1.06 μ could not be obtained.

[b]Both the unexposed color transparency and the fully exposed black and white film had differing thresholds depending on the side exposed. The thresholds listed are for the most sensitive film sides: the emulsion side for the Panatomic X and the nonemulsion side for the Kodachrome II.

[c]The visible response noted was a darkening of the paper. The responses of these papers varied depending on previous exposure to ambient light.

[d]The visible response noted was a change in surface finish from a dull black to a glossy black.

Note: The visible change is normally a lightening of the surface unless noted. Preliminary measurements of the sensitivity of black Polaroid print film to non-Q-switched exposure indicated an increase in threshold of approximately one order of magnitude. Saturation levels are provided only for the minimal type of surface change. In most cases more striking changes occur at still higher radiant exposures.

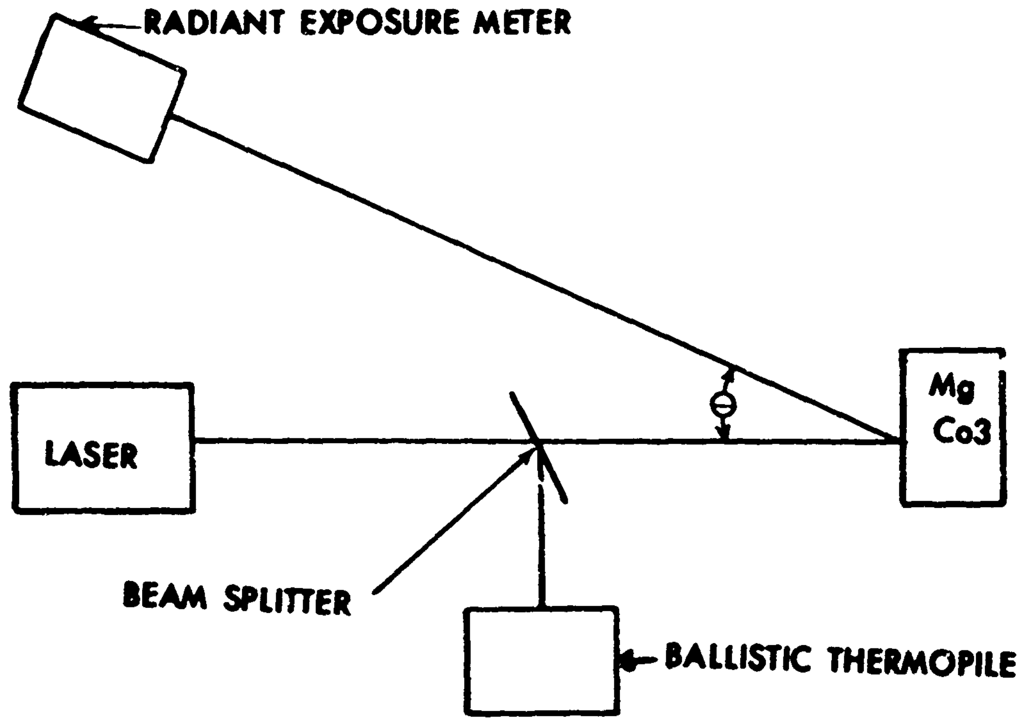


Figure 7. Arrangement for Calibrating a Radiant Exposure Meter Against a Calibrated Ballistic Thermopile using a Single Mode Laser. For a laser which changes modes and therefore changes beam polarization, the fraction of energy deflected by the beam splitter will change unless the beam splitter is positioned at near-normal incidence and the ballistic thermopile positioned near the laser.

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OCULAR EFFECTS OF LASER RADIATION: CORNEA AND ANTERIOR CHAMBER

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The effects on cornea and skin of infrared laser radiation are based upon the absorption of energy from these sources and the resultant "thermal" alteration of tissues. In the evaluation of these effects, the two tissues must be considered together since both the cornea and skin are derived embryologically from surface ectoderm and mesoderm, and are most accessible to interception of radiation and absorption of radiation. This presentation will center on the surface tissues of the human organism, namely cornea and skin (9). The first phase will emphasize the normal anatomy and physiology of both tissues. The second phase will involve the superficial summary of those laser systems which may interact with these tissues, and finally the effects of alterations from these systems will be discussed.

During the past five years research into the comparative effects of infrared laser radiation and incoherent radiation on skin and cornea have been reported (1-9). The threshold levels necessary to provide permissible exposure levels for personnel working with these laser sources have been primarily derived from characteristics of solar radiation in the infrared and extrapolation involving variables in the "normal" environment from solar radiation. Characteristics of infrared laser exposure and tissue thresholds are required for comparison with other incoherent source data for a more precise safe level determination. The early data (1-4) was concerned with laser effects to ocular tissue. The comparative thresholds to skin must be presented and determined (5-9).

The obvious transparency of the primate cornea is due, in part, to the regular arrangement of the fibers of the substantia propria or stroma. Characteristic of the histology is the epithelium, approximately 50 microns thick, a condensed layer (Bowman's membrane) 5-10 microns, a dense stromal area (500 microns), Descemet's membrane (5-10 microns) and an essential monolayer, the endothelium (5 microns). The total corneal thickness is approximately 550-600 microns. The cornea is vessel-free, with an extensive supply of pain endings. Alterations to the epithelium produce a rapid response to reepithelization and recovery. A surface tear film approximately 7-10 microns covers the epithelial surface. Although viable, the entire corneal thickness is transparent. Laser exposure may produce temporary to permanent changes in this light conductivity.

Unlike the cornea which varies slightly from eye to eye or individual, skin thickness may vary widely from 0.4 millimeters to 5 millimeters depending upon location on the body surface. Additionally, pigmentation varies widely across the body areas as well as among peoples. Basically, the surface layer composed of nonviable keratinized cells (stratum corneum) is 15 microns in thickness. The underlying viable epidermis has a thickness varying from 50-75 microns and consists of strata including a thin, relatively homogeneous layer (lucidum), diamond-shaped cells containing keratohyalin granules (granulosum), polyhedral shaped cells (spinosum) and the deep columnar epithelial cells (germinativum). Again unlike the cornea, cell division occurs in the deep germinal layer and progress toward the surface. Replacement of loss of cells must progress from deeper layers. Corneal morphology diverges from these characteristics in that epithelial cells are viable and subsequent layers appear to be autogenous in the developmental cycle.

Currently, relevant laser wavelengths include neodymium (1.06 microns), erbium (1.54 microns), holmium (2.06 microns), hydrogen and deuterium fluoride (2.79 and 3.83 microns), and carbon dioxide (10.6 microns). These wavelengths correspond to absorption characteristics which indicate surface or near surface alterations.

When investigating the effects of monochromatic radiation, the Lambertian absorption coefficient, which is wavelength dependent, and surface reflectivity are important variables to consider. The proportion of the incident radiation transmitted to a given depth of z is given by e^{-az} where a is the Lambertian absorption coefficient. The higher the absorption coefficient the larger the quantity of energy absorbed in a smaller volume. This can result in extensive injury to the most superficial layers. The smaller the absorption coefficient the larger the volume of tissue available to dissipate the energy; however, this permits penetration to the underlying tissue structures. Heat conduction through the tissue must be considered as a means of altering the surrounding tissue. Since the cornea and skin are aqueous in nature, the absorption coefficient of water is a good first approximation. The absorption coefficients for the relevant infrared lasers are as follows:

Laser	Wavelength (microns)	Absorption Coefficient (centimeter^{-1})
Erbium	1.54	19
Holmium	2.06	90
HF	2.79	4,900
DF	3.73	115
CO_2	10.6	815

The direct utilization of these numbers enables the scientist to estimate the equivalent depth of absorption.

The biological interpretation of data generated by the research into threshold levels is aided by the understanding of the interaction of laser energy and a degree of comprehension into the physics of Lambertian absorption. The ultimate goal of the work is to establish an extrapolation to protection standard levels derived from subhuman and vertebrate exposures. Additionally, the following areas will provide an appreciation for those variables which are important in this research. They include:

1. Wavelength.
2. Beam geometry both the spatial intensity distribution and the irradiance diameter.
3. Calibration and dosimetry.
4. Pulse duration and repetition rate.
5. Tissue characteristics.
6. Endpoint (time after exposure).
7. Criteria for alteration of tissue.
   a. Gross
   b. Microscopic
      (1) Light microscope
      (2) Electron microscope
8. Statistical analysis of data.

Threshold damage to the eye from CO_2 laser radiation is confined to the more superficial areas of the cornea. Utilizing the absorption coefficient (815 centimeter^{-1}). Ninety-nine percent of the energy will be absorbed within the first 55 microns. The absorption will occur then in the tear film (7 microns) and epithelial layer (50 microns). The criteria for corneal injury is the presence of gray-white opacity at the site of exposure observed with the slit lamp biomicroscope 24 hours after exposure. The energy for each exposure was varied to determine the threshold level and data was analyzed by the technique of probit analysis. Data for the following pulse duration and ED_{50} levels are given as follows:

Pulse Duration (milliseconds)	ED_{50} (watts/centimeter^2)
1	800
2	485
10	72.5
1,000	7.7
5,000	3.0

Minimal corneal alteration was completely reversible within 24–48 hours. More subtle threshold determinations of alteration occur in the utilization of trypan blue staining of exposed corneal tissue. This technique, well known in clinical keratoplasty techniques, allows the survey of the critical viability of the corneal endothelium. At or near threshold levels, extensive staining of the endothelium (indicating alteration in biochemical cell process) raises the subtle question of endothelial repair and the additional finding of missing endothelial cells at the center of the carefully prepared specimens questions the survivability of the exposed tissue.

The threshold for Q-switched erbium laser radiation is approximately 20 joules/centimeter^2. The characteristics of this radiation (absorption coefficient - 19 centimeter^{-1}) indicate that energy absorption (99 percent) would be expected to occur in 2.42 millimeters. At above threshold levels, damage was observed to be full thickness penetrating deep into Descemet's membrane and endothelial layer. Some changes in the anterior chamber were observed. The endpoint was 24 hours post-exposure appearance of opacity.

The subtle interpretation of threshold levels of radiation to skin is based upon a divergence from classical grading of clinical burn data. At or near the threshold levels a system utilized by the investigators involves the classification of grades of erythema (reddening of the exposure site) with or without concomitant stratum corneum (white burn) involvement or oblating of the surface layers. Further histopathological analysis of exposures is hampered by the presence of chronic dermatoses of porcine skin as well as preparation artifacts prior to exposure. The data presented for porcine skin exposures observed grossly at 1 hour and 24 hours post-exposure is as follows:

Pulse Duration (milliseconds)	ED_{50} (watts/centimeter^2)
4.3	247
39.0	37.5
220	13.6
300	10.6
370	7.6
710	4.7
306	3.7
4,100	1.7

Utilizing similar exposure criteria, porcine skin was exposed to erbium radiation in the range between 8 joules/centimeter^2 and 80 joules/centimeter^2. A total of 148 exposures were made in five pigs. No erythema was observed in any of the exposures at the 24 hour level for any of the energy densities ruling out the analysis of the ED_{50} level.

In [illegible]ium dosimetry, it was necessary to focus the output energy onto the tissue to permit energy densitie[illegible] of producing corneal alterations.

The interpretation of corneal exposure experiments mandates further evaluation of the significance of the corneal endothelial alterations. In addition, the effects of low level continuous and repeated pulsed radiation for these infrared laser sources is necessary. The completion of these studies will add vital information to the knowledge of corneal response mechanisms to laser radiation. The effects of exposure to continuous exposure within present safe level environments must be kept in mind for the existent possibility of long term chronic effects due perhaps to cumulative absorption, or the future sequelae of direct effects on corneal endothelium or stratum germinativum of the skin. It must also be understood that the present expertise and research will continue to modify whatever safe levels are postulated.

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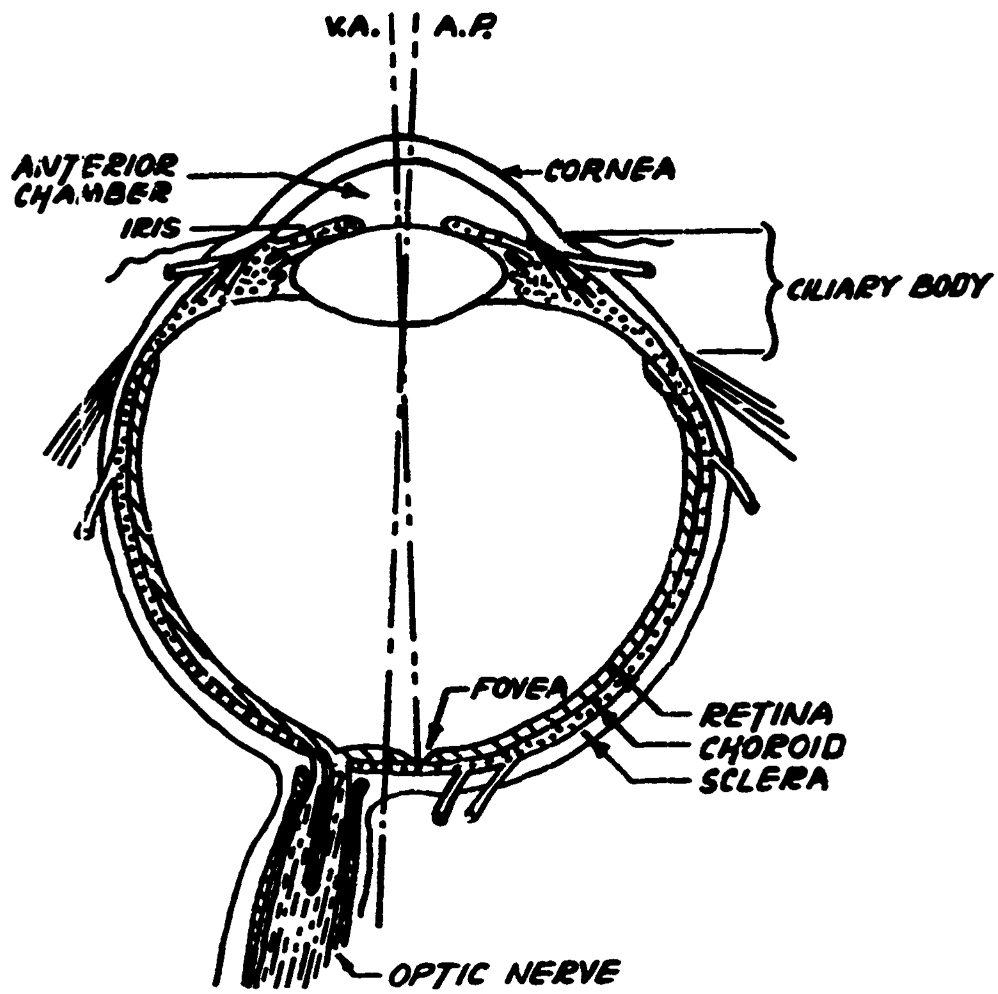
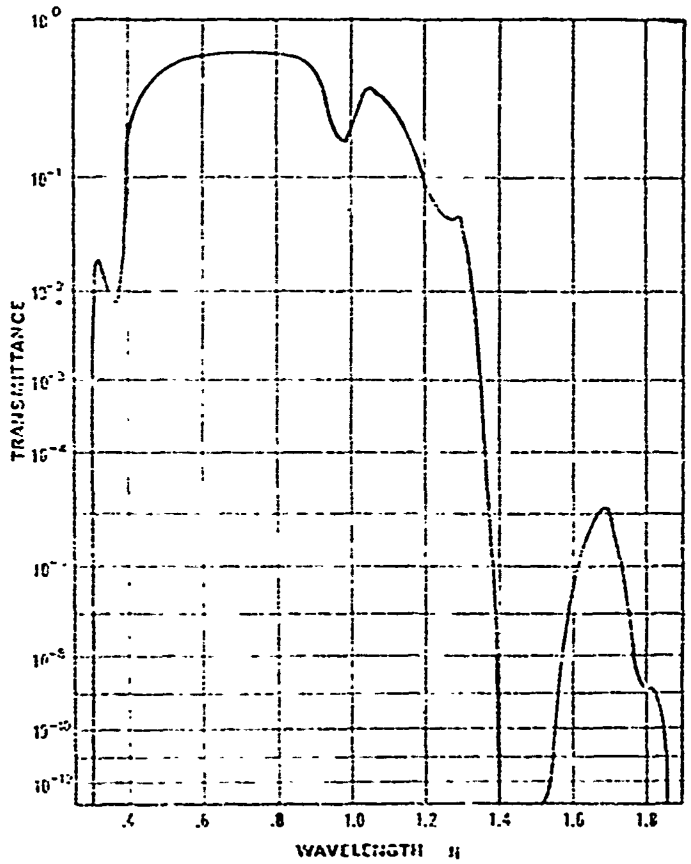
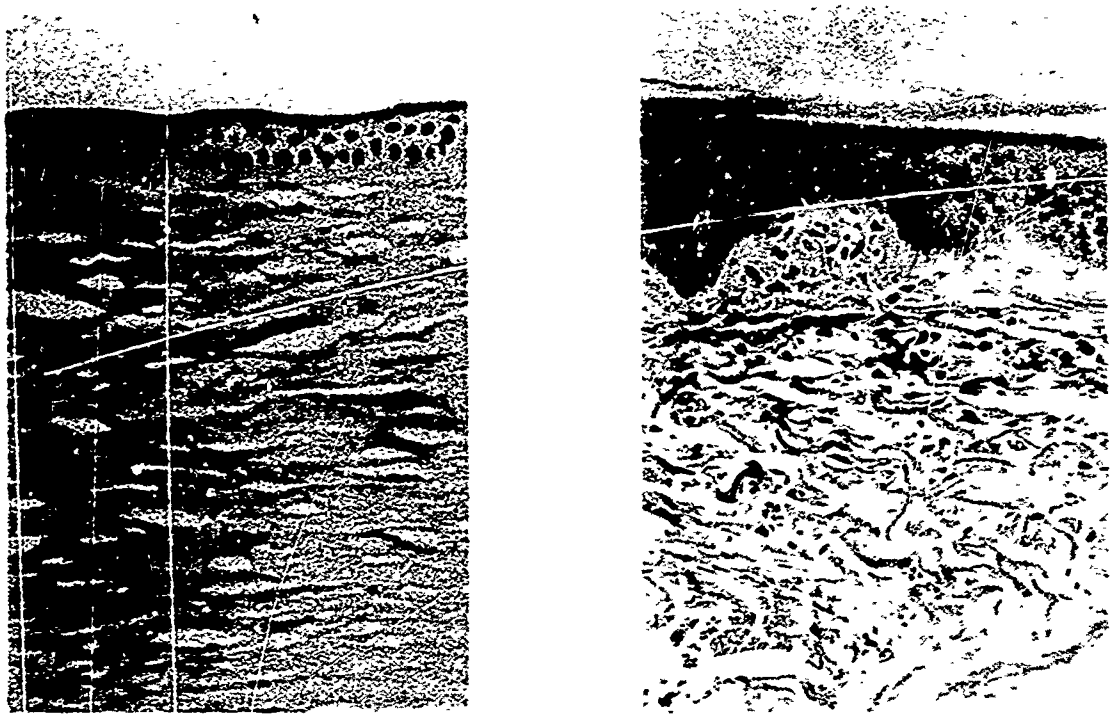


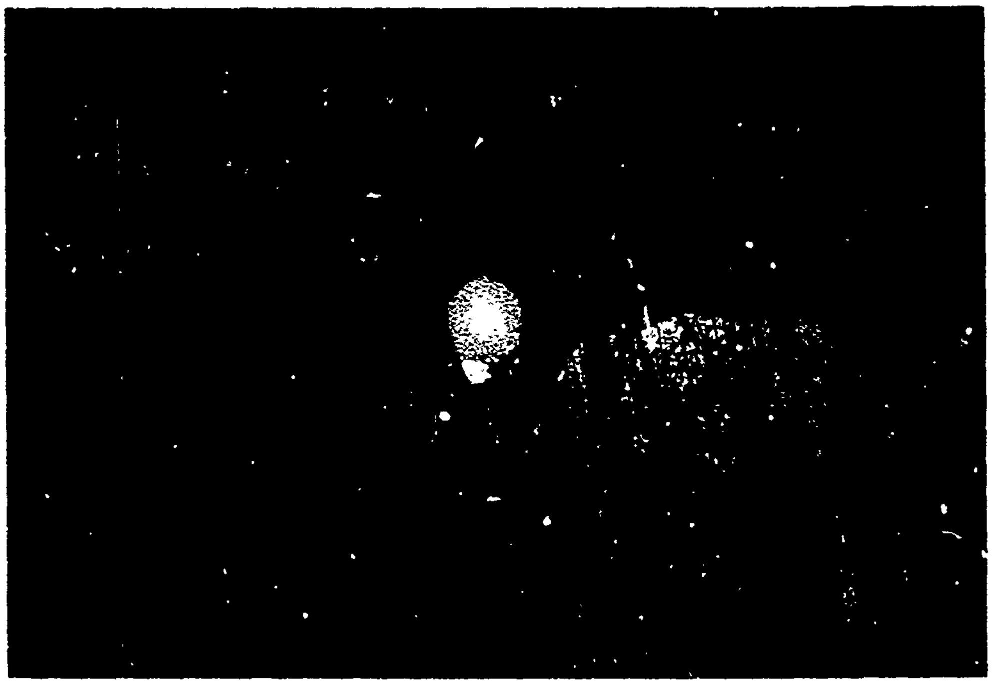


Spectral Transmittance Through Human Eye



A B

Serial sections of rhesus cornea (A) and porcine skin (B). Note corneal epithelium and interwoven stromal pattern, as well as dermis and epidermis of skin.



Carbon dioxide exposure to rhesus cornea at 65 watts/centimeter^2 - 100 milliseconds. One hour post-exposure. Stromal clouding is evident in this time frame.

OCULAR EFFECTS OF RADIATION: RETINA

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A summary of the endpoints used in establishing threshold levels for visible and near infrared laser exposures to primate retina will include: review of normal retinal histology, funduscopy (ophthalmoscopic), light microscopic and ultrastructural criteria. Some preliminary correlation will be made with behavioral-psychophysical measures. The discussion will indicate a need for continued study in the interface between gross alteration (opacity) and behavioral evaluation.

The requirement to establish safe operating levels for the use of lasers in the military and civilian communities has resulted in extensive biomedical experiments involving subhuman primate subjects. During the past ten years, extensive research on the effects of visible laser irradiation on the primate and vertebrate retina has been conducted in various laboratories (1-10). A partial review of the "normal" funduscopy and histopathology of the primate retina will provide a base from which alterations can be demonstrated and compared with other biological and environmental processes affecting the retina.

Ophthalmoscopically, the posterior pole of the primate eye is characterized by the optic disc (non-pigmented), superficial retinal vasculature and the macula. This latter portion of the retina is the focus of vision and of the ocular hazard from laser radiation. The macula in primates is relatively large. It measures two millimeters in diameter and the fovea approximately 200-250 microns. In the fovea, the cone photoreceptor density is the greatest (approximately 147,000 per millimeter^2).

All superficial elements of the retina (sensory retina) are "transparent" such that the view of the posterior pole or fundus results in an observation of the retinal pigment epithelial monolayer. At the gross clinical observation level, data can be derived while some questions as to retinal sensitivity may be resolved by microscopic evaluation of the exposed tissue. For this information, attention must be directed to retinal histology.

The retina is subdivided into ten identifiable layers. In the path of incoming light, the layers include: the nerve fiber layer, ganglion cell layer, inner plexiform layer, inner nuclear layer, outer plexiform layer, outer nuclear layer, rod and cone layer, and pigment epithelial layer. The absorption site of the visible and near infrared laser sources is the melanin granules of the retinal pigment epithelium. The mechanism of injury at the above threshold exposed site is "thermal."

Laser sources, which will be transmitted to the retina, include the wavelengths from approximately 400 to about 1,400 nanometers. In the range between 500 and 900 nanometers, the maximum transmission of light occurs (approximately [illegible] percent). Lasers of current interest include: continuous wave argon (488 and 514.5 nanometers), neodymium (1,060 nanometers), and pulsed ruby (694.3 nanometers).

The endpoint for the determination of threshold levels can be subdivided into three areas. These include: grossly observable retinal opacity level, light microscopic cellular alteration at the distal photoreceptor and pigment epithelial level, and subcellular change at the magnification power of the electron microscopic level. Emphasis has been on the clinically observable opacity. At times ranging from one to 24 hours after exposure, the ophthalmoscopic criteria of the appearance or persistence of a gray-white opacity is the evidence of retinal alteration.

Table I

Laser (source)	Wavelength (nanometers)	Pulse Duration (milliseconds)	Energy (microjoules)	Retinal Irradiance (microns)
Ruby	694.3	30 x 10^{-9}	16.9	50
		30 x 10^{-9}	104	500
		30 x 10^{-9}	202	1,000
Neodymium	1,060	20 x 10^{-9}	409	60
			327	100
			1,815	500

Threshold opacity levels are shown for corresponding irradiance diameters for Q-switched ruby (694.3 nanometers) and neodymium (1,060 nanometers) sources. For both sources, threshold levels increase as retinal irradiance diameter increases. The absolute threshold levels shown for neodymium are consistently higher than those for ruby. The energy density required to produce a threshold opacity decreases monotonically as the retinal irradiance is increased.

Table II

Laser (source)	Wavelength (nanometers)	Pulse Duration (milliseconds)	Power (milliwatts)	Retinal Irradiance (microns)
Argon	488	1.5	51	30
		80	13	30
		13.5	49	200
		80	34	200

The data in Table II shows the relationship for an argon source (488 nanometers) for two retinal irradiance diameters (30 and 200 microns).

Several techniques enable investigators to develop and access threshold data by utilizing the light microscope. Comparisons of equivalent exposures by direct observation and light microscopy for argon, 514.5 nanometers, 125 milliseconds and ruby, 694.3 nanometers, 30 x 10^{-9} seconds indicate a reduction in ED_{50} levels of 30 percent using the serial sections and subtle RPE endpoint. The limit of detectability at the morphological level is, of course, the electron microscope where alterations observed for Q-switched ruby by EM techniques is ten times lower than the clinically observable ED_{50} level.

Further follow-up of low level Q-switched ruby exposures ten times below ED_{50} levels indicates not only marked ultrastructural alterations, but persistence of these alterations for up to 18 months after initial exposure. Autoradiographic retinal techniques of similar exposures indicate the blockade of protein synthesis in retinal rods (radioleucine).

Threshold opacity levels also have been shown to depend upon exposure site and retinal pigmentation. The macula has been reported to be more sensitive, by a factor of two, than paramacular sites. Increased sensitivity is found in the area immediately temporal to the macula at both argon and ruby wavelengths. As exposures are placed increasingly off-axis, the optical limitations of the eye degrade the image quality, producing aberrant opacities (if the beam is characteristically TEM_{00} central exposures produce circular opacities; off-axis exposures produce ellipsoidal opacities).

Morphological experiments are routinely performed in the anesthetized, emmetropic dilated animal eye. These conditions, while producing controlled exposure techniques, are far removed from the simulation of the accident exposure situation.

The general anesthetic used depresses the central nervous system, reducing the ability to detect the important neural signals which may indicate alteration in the photochemistry at levels far below opacity criteria levels while the first approximation of opacity may be important. The long term significance of absence of opacity in the possible presence of depressed electrophysiological signals will be of more significance.

As the retinal layers represent a critical link in the photochemical and neural events associated with the visual process itself, permanent alterations to any or all of the retinal layers may produce permanent changes in the visual process. Recent investigations of visual function suggest that intense laser exposure can severely alter the visual process. Foveal exposures above threshold can produce permanent changes in both maximal visual acuity and color vision (10). Permanent changes in the visual systems ability to dark adapt may also be associated with foveal irradiation. Furthermore, it seems that as was the case for morphological criteria, as functional criteria are refined, laser energy levels at which minimal alterations occur tend to be lower.

Future experiments will, no doubt, include subtle investigations of changes in morphological and functional criteria and laser energy levels at which such effects occur will be obtained at levels much lower than those observed for grosser criteria.

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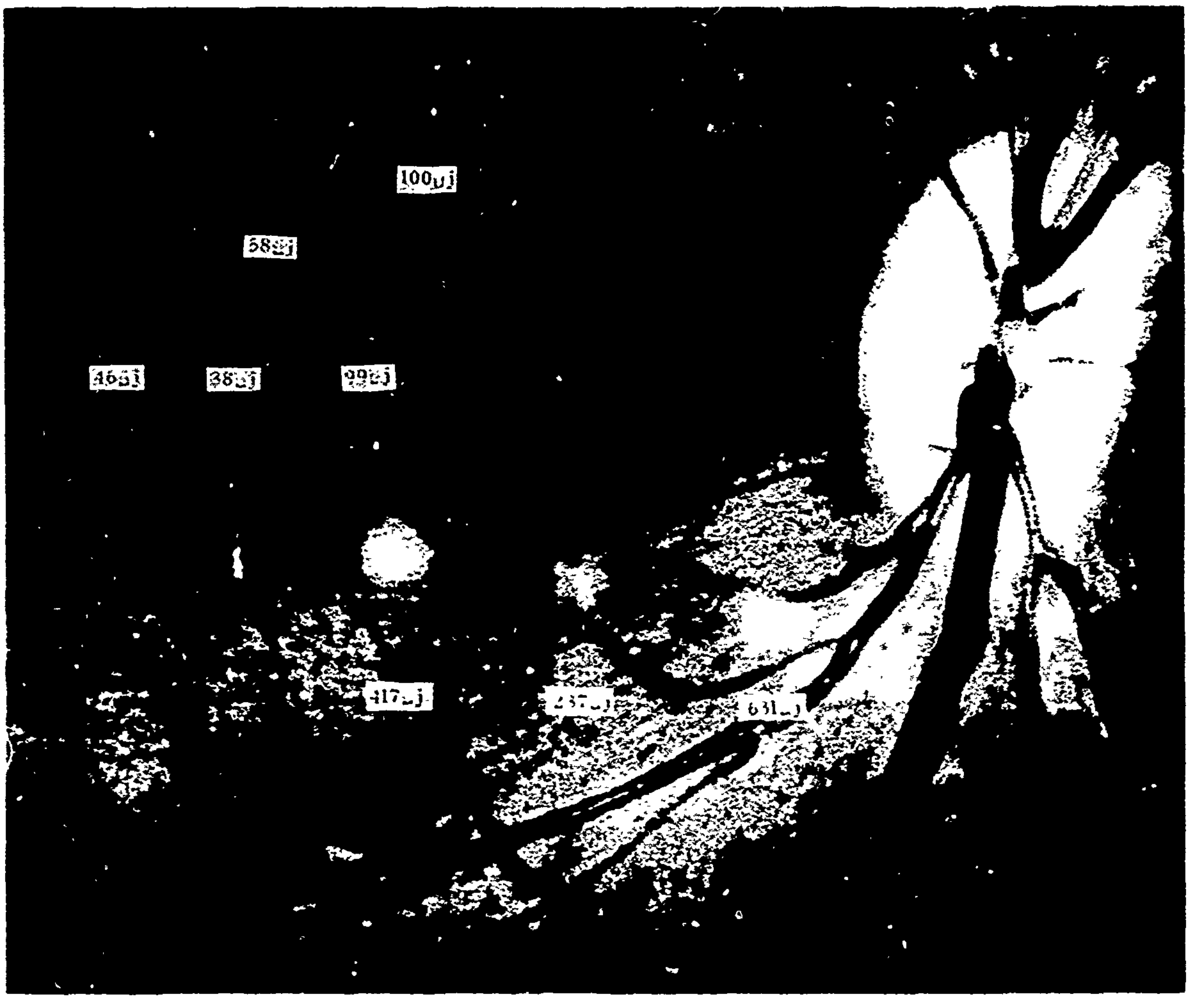
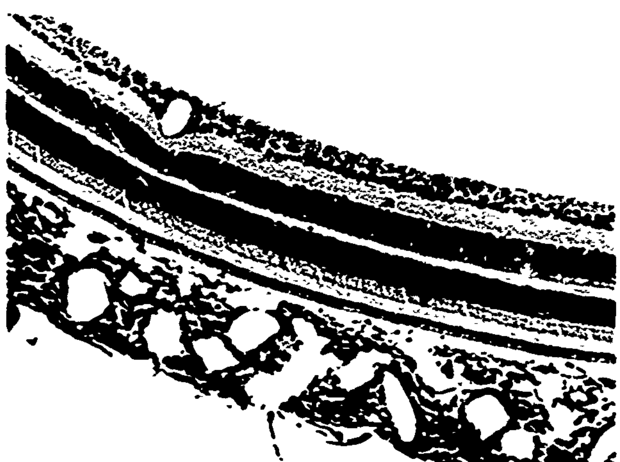
Two individuals have been helpful in the preparation of the lecture notes for the lecture series. They are: LTC Horace Gardner, Chief, Combat Surgery Division, Letterman Army Institute of Research, acknowledged for his thoughts and assistance in the preparation of the lecture notes, and Dr. Harry Zwick, Research Psychologist, Letterman Army Institute of Research, who provided valuable assistance in the development of the lecture notes and the added section on the psychophysics of vision.



Fundus photograph of rhesus retina one hour after varying exposures to Q-switched ruby radiation. Total energy at cornea is indicated for each exposure.



Normal appearance of rhesus retina as observed by light microscopy.

A

B

C

(A) Light micrographs of acute Q-switched neodymium retinal exposures (1,320 microjoules). Note disruption of pigment epithelial cells and vacuole in subretinal space.

(B) Note distortion and disarray of inner and outer segments of photoreceptors and changes in pigment epithelium (478 microjoules).

(C) Electron photomicrograph shows altered photoreceptor vesicle and whorl formation not evidenced by direct observation or light microscopy (40 microjoules).

DETERMINATION OF SAFE EXPOSURE LEVELS: ENERGY CORRELATES OF OCULAR DAMAGE

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SUMMARY

Practical, but safe criteria, for use of laser systems require an understanding of tissue damage, and three techniques have been used to define energy correlates for safe exposure levels. Inspection of the eye by optical means (ophthalmoscopy) has provided the basis of minimal visible damage for many studies, fluorescein angiography has explored the disturbance of the blood-retinal barrier induced by laser irradiation of the retina, and microscopy (light and electron) has attempted to define the energy correlates for minimal structural change. The detection of damage is a form of quantal response and the determination of the threshold level is normally based on the energy or power which will result in a given probability of damage being detected.

The energy correlates of damage depend on wavelength, pulse width or exposure time, repetition rate, tissue type and pigmentation, and ocular quality. This complex relationship necessarily limits experimental research to laser systems of special interest and so the interpolation of data to formulate overall safe exposure levels is necessary.

INTRODUCTION

Until recently laser operations tended to be confined to the laboratory and protective eye wear with engineering controls provided adequate personal protection, but with the increasing use of lasers for both military and civilian purposes in less well controlled circumstances careful consideration of safe viewing distances is essential. The initial step in the establishment of safe exposure levels is to determine the energy correlate of threshold damage. Only two structures need be considered at risk from laser radiation - the eye and the skin - but the eye is of primary concern, as even a minimal damage to the eye may impair visual function.

Damage Mechanisms. The primary event in any type of tissue damage caused by laser radiation is the absorption of energy in the biological system. The absorption of the photon of incident energy occurs at an atomic or molecular level and is wavelength specific. The process can result in the general increase in the vibrational energy of the molecule which gives rise to an increase in temperature (thermal damage) or can change the inter-molecular bonding within the material and give rise to a chemical change (photochemical damage). Both processes can change the tissue components (denaturation) so that the biological function of the tissue is impaired. Far infra-red radiation usually produces thermal damage, while the far ultra-violet radiation leads to photochemical changes. Between these regions the near infra-red and visible light may produce either type of tissue damage (Fig. 1). Within the radiation band 400 - 1400 nm the eye transmits and focuses the energy on to the retina and so concentrates the energy incident on the cornea by several orders of magnitude. Outside this band the eye is virtually opaque and the energy is absorbed by the cornea, lens and transparent media. It is advantageous to consider threshold studies in two parts ie. damage to cornea and lens damage to the retinal structure.

CORNEAL STUDIES

UV Radiation. At the present time there is little reliable data on the biological effects of UV laser radiation. Vassiliadis et al (Ref. 1) using a Q-switched frequency doubled ruby laser (λ = 347 nm) demonstrated that the primary absorption site at this wavelength was the lens. Maclean et al (Ref. 2) used a helium cadmium laser (λ = 325 nm) but did not observe any lenticular changes. While there is a lack of experimental evidence of damage from laser sources, a considerable amount of data has been obtained using conventional UV sources. As early as 1916 Verhoeff & Bell (Ref. 3) published a comprehensive review of UV hazards and showed that at wavelengths shorter than 305 nm damage was to the cornea and corneal epithelium, with confined widespread changes in the lens capsule. Cogan & Kinsey (Ref. 4) demonstrated the peak sensitivity of corneal tissue at an incident wavelength of 288 nm and determined the threshold dose to be 5 millijoules/cm2. They also stated that the tissue damage was dependent on total energy and not on the rate of absorption. More recently Pitts (Ref. 5) in an extensive review of the problem of UV radiation and a detailed research programme has quantified the effects of UV radiation within the band 210 - 330 nm in the threshold production of photokeratitis.

Middle and Far Infra Red (1400 nm - 100 µm). Within this waveband there are three main lasers that are likely to be of importance. The CO_2 laser at 10.6 microns, the holmium at 2.06 microns and the erbium at 1.54 microns. Radiations from all these laser types are absorbed by the aqueous content of the cornea and the pre-corneal tear film.

Fine et al (Ref. 6) have studied the long term effects of exposure to 10.6 micron radiation and report changes to the corneal structure and appearance at levels of about 0.5 watts cm^{-2} for periods of 5 minutes with no damage after exposure to less than 0.1 watts cm^{-2} for periods of up to 30 minutes. Campbell & Rittler (Ref. 7) report the production of just detectable damage from the CO_2 laser after exposures of 3.85 watts/cm^2 for 3 seconds and Leibowitz & Peacock (Ref. 8) studying shorter exposure times give a threshold of 15.6 watts/cm^2 for an 80 millisecond exposure. Peppers et al (Ref. 9) report figures of threshold damage of 18 watts cm^{-2} in 70 milliseconds and Gulberg & Hartman (Ref. 10) studying the production of a blink reflex quotes a formula - Q (joules cm^{-2}) = 1.26 t (secs) for exposures within the time range 0.01 to 5 seconds. This is in reasonable agreement with the work of Borland et al (Ref. 11) who state that the corneal threshold level is 6.9 watts cm^{-2} for a 70 millisecond exposure. This not

inconsiderable spread of experimentally determined threshold levels can to a large extent be attributed to differences in the experimental techniques ie dosemetry and the matter of detecting minimal damage.

No threshold data is available for the holmium laser and only one group, Bresnick et al (Ref. 12) have studied the erbium laser for which they report a corneal threshold of 17 joules/cm^{-2} for the 50 nanosecond Q-switched pulse.

RETINAL STUDIES

Visible and Near Infra Red Threshold Studies (400 - 1400 nm). The majority of lasers of military and civil importance radiate in this part of the electromagnetic spectrum (except CO_2 laser at 10.6 microns) and it is hardly surprising that the majority of laser safety studies have been concentrated within this waveband, where the retina of the eye is at risk.

In considering threshold damage to retinal tissue four main factors must be taken into account. These are - a definition of threshold, wavelength, exposure time and image size.

Damage to retinal tissue following laser radiation can be detected in one of four ways of which ophthalmoscopy is by far the most common and has provided the basis for 'minimal visible damage' studies. The development of an ophthalmoscopically visible lesion is time dependent and although a one hour post exposure criteria is commonly applied in experimental studies some lesions may not become visible for up to 24 hours post exposure. Ophthalmoscopy is at best a means of establishing a baseline for comparing experimental studies, the detectability of lesions being dependent on the type of ophthalmoscope used, the skill of the observer and the image size being observed. A second and more sensitive technique in the detection of minimal damage is that of fluorescein angiography which can demonstrate small disturbances of the blood retinal barrier induced by the 'thermal' reaction to laser irradiation. Fluorescein angiography is three or four times more sensitive in detecting lesions than ophthalmoscopy but still represents a relatively severe level of damage in the pigment epithelium and receptors and while there is evidence that several months post exposure the site of a fluorescent lesion has showed histologic evidence of structural recovery, there is no direct evidence that the functional integrity of the retinal organisation has been repaired. It is therefore necessary to use electronmicroscopy as the final endpoint on which to base safe exposure levels in order that both permanent and temporary damage to the retinal structure may be avoided.

Some studies, McNeer et al (Ref. 13) and Davis & Maultner (Ref. 14) have reported on the effects of laser radiation on the electrical responses of the eye. However, although the energies required to produce minimal electrical disturbances are less than the ophthalmoscopic threshold levels they appear to be higher than the electronmicroscopic threshold levels as determined by Adams (Ref. 15) and Landers et al (Ref. 16) and Borland (in preparation).

Wavelength. Fig. 2 illustrates the percentage of the radiation incident on the cornea that is absorbed in the pigment epithelium and choroid of the rhesus monkey, the most commonly used experimental animals, rabbit and human. Radiation within the band 400 - 700 nm are also absorbed by the photo-pigments within the receptors and evoke a visual response and although in general it is the melanin granules of the pigment epithelium which provide the absorption site for the incident radiation, prolonged exposure to radiation within the visible part of the spectrum can induce retinal damage that cannot be related to the normal thermal damage mechanisms.

Time. Ocular exposure to laser radiations may extend from continuous viewing over a period of several minutes or hours to a single mode locked pulse lasting fractions of a picosecond. Not surprisingly over this range of exposure times the mechanism of damage does not remain constant. Sperling (Ref. 17) has shown how prolonged exposure to the argon laser radiation can produce permanent impairment of the spectral response to the rhesus monkey eye while Noell et al (Ref. 18) using rats and Marshall et al (Ref. 19) using pigeons have demonstrated how even fluorescent lighting at moderately high levels can produce profound retinal degeneration over periods of several hours. This mechanism of damage is not yet fully understood but it would appear to be a 'poisoning' of the receptors by a prolonged generation of the by products of the photo-chemical processes. For exposure times of less than 100 sec down to times as short as 10 micro seconds the damage to retinal structure is due solely to localised tissue heating. Several research groups have studied this time domain and the Stanford Research Institute (Vassiliadis et al), the Joint Laser Safety Team (Beatrice et al) and the Medical College of Virginia (Ham et al) have used a wide range of laser wavelengths and exposure times and have shown a remarkable degree of agreement.

Studies at times shorter than 10 microseconds have been limited to the Q-switched ruby and neodymium systems and to the pulse argon system. Data from the main research groups again show a remarkable agreement but the data when compared with the results from the longer exposure periods indicates that a different type of damage mechanism may be present and it has been suggested that the damage observed is caused by acoustic transients generated by the rapid expansion of the retinal tissue as a result of the sudden temperature rise induced by the very short pulses, (Marshall et al, in preparation).

Retinal Image Diameter. The retinal image size and the corresponding energy distribution are important factors in determining the time/temperature relationship involved in thermal damage studies. For an ideal eye accommodated to a laser wavelength, the image size will be equal to the product of the eye's focal length and the divergence of radiation incident on the cornea. As the beam divergence reduces, that is the laser becomes an effective point source, the image size reduces until theoretically limited by diffraction. The distribution of energy in the plane of the geometrical focus is the well known Arey disc surrounded by concentric bright and dark rings. The diameter of the retinal image across the first dark ring is given by the formula $\frac{2.44\lambda f}{nd}$ where λ is the wavelength in microns, f is the second focal length of the eye in mm (22.9 for human case), n is the refractive index of the ocular media (1.334) and d is the pupil diameter in mm, thus for a 7 mm pupil the perfect 'eye' would be capable of producing a retinal image diameter some 6 wavelengths in diameter. However the eye is not a perfect optical system and contains aberrations. The eye is unlikely to be corrected for the wavelength of the incoming radiation. The effect of spherical aberration tends to compensate for the reduction in image size due to diffraction with increasing pupil

diameter, an empirical approach to the point image spread function has been made by Mayer et al in Ref. 20. A more exact approach to the problem of the distribution of energy across the retinal image and the limiting retinal image size is to consider the Optical Modulation Transfer Function which quantifies the performance of any optical system in terms of the ratio of the corneal energy distribution to the retinal energy distribution. Several researchers, Campbell & Gubisch (Ref. 21), Westheimer (Ref. 22) and A. van Meeteron (Ref. 23), have studied this problem in the living human eye for both white and quasi monochromatic sources, but as yet however no studies have been made on the modulation transfer function of the eye of the rhesus monkey or rabbit, the two species commonly used in the determination of retinal threshold levels. In the rhesus monkey Stein & Elgin (Ref. 24) have reported in vivo estimates of minimal image size for white light of some 30 microns while Vassiliadis et al (Ref. 25) report estimates of minimal image diameters of 90 microns at the neodymium wavelength and some 50 microns at the ruby wavelength. In the rabbit eye Ham et al (Ref. 26) have noted how the poor optical quality causes an increase in the apparent energy per unit area necessary to cause threshold lesions with decreasing image size. Additionally, Jones & Fairchild (Ref. 27) have shown that the Optical Modulation Transfer Function not only limits the image size and degrades the retinal image distribution but also affects the ability to detect damage viewed through the reverse optical path.

When the observed damage is thermal in origin the basic considerations of heat transfer indicate that heat is conducted away more slowly from the central portion of a large area irradiance than for a smaller area and consequently it is to be expected that a lower threshold for damage will be found (in terms of retinal radiant exposure) for the larger irradiance diameters. Several mathematical models have been put forward which provide excellent agreement with the experimental data for image sizes of from 10 - 1000 microns and over a time scale of from several microseconds to seconds, and a complete review of thermal modelling has been presented by Wolbarscht (Ref. 28). Beatrice & Frisch (Ref. 29) have demonstrated how a similar dependence of threshold image diameter is found for both 1 sec argon exposures and 30 nanosecond Q-switched ruby exposures. As yet no satisfactory model has been put forward which will explain all the observed results especially those related to the Q-switched time domain where the retinal threshold level is also dependent on image size which is contrary to the basic principles of heat transfer. This supports the view that damage to retinal tissue by Q-switched irradiation is not purely thermal in origin.

Determination of Threshold. The experimental determination of a threshold level involves the detection of the absence or presence of a response in a subject to a known exposure level or stimulus. The characteristic response is said to be quantal if the occurrence or non occurrence depends on the intensity of the stimulus. For a particular retinal site there will be a level of stimulus below which the response does not occur and above which the response always occurs; this stimulus level is called the threshold. The threshold level will vary between retinal sites and between subjects within the population studied. The analysis of quantal response data is best carried out by a statistical technique called Probit Analysis, Finney (Ref. 30). Results are presented as a linear regression line of damage probability plotted against the logarithm of the dose. The dose corresponding to a 50% probability is termed the ED_{50}, and is commonly quoted as the "threshold level". Probit analysis also provides the normal statistical evidence as to the significance that can be placed on the results. Fig. 3 shows a typical regression line, with 95% confidence limits on both ED_{50} value and slope.

The data is for Q-switched neodymium irradiance of the rhesus monkey eye, with an image diameter estimated at 30 microns.

Probit analysis also allows a comparison to be made either between the effectiveness of different stimuli (laser parameters), or between differences in the response within the same population to the same stimuli. Fig. 4 shows the regression lines for damage as determined by ophthalmoscopy and fluorescein angiography in response to Q-switched neodymium laser radiation. The ED_{50} values are significantly different, and show that fluorescein angiography is a more sensitive technique in detecting threshold damage than ophthalmoscopy.

A single experiment to determine an ED_{50} level for a particular type of laser radiation does not in itself provide a basis for the derivation of safe exposure levels. However, an understanding of the major factors affecting damage together with data from experiments involving similar laser parameters are essential ingredients in the formulation of safe exposure levels.

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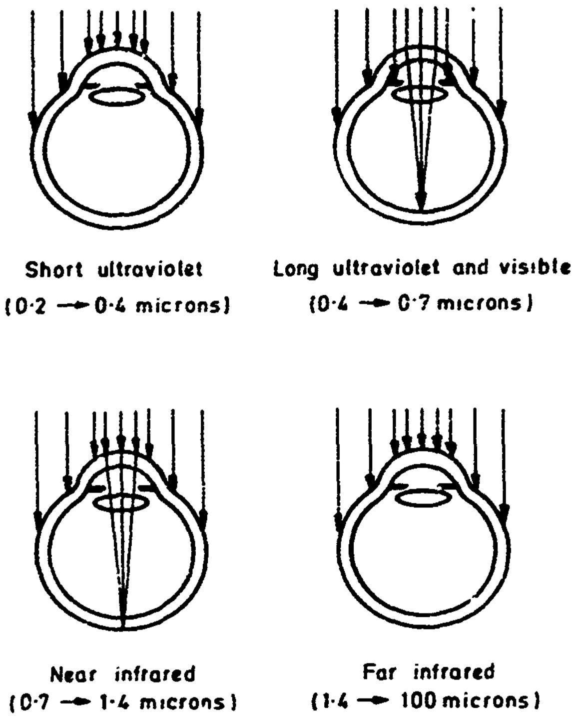

Fig.1

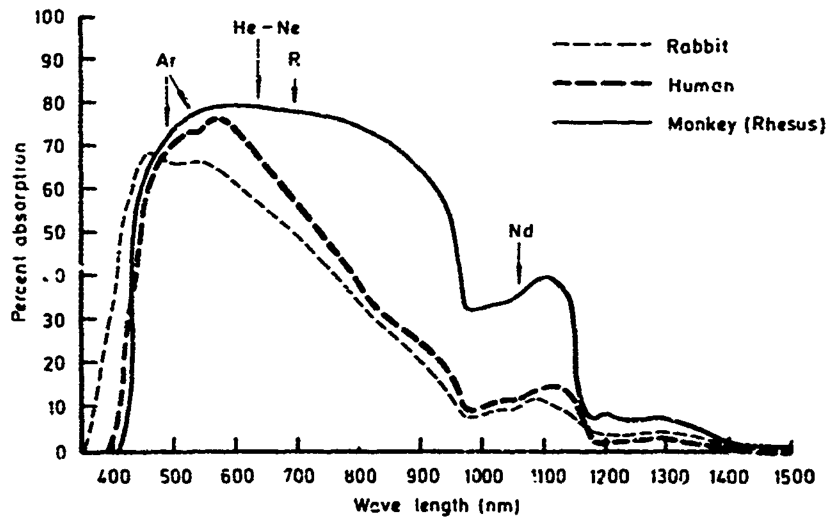

Fig. 2
Percentage of light incident on the cornea that is absorbed in the retinal pigment epithelium and choroid

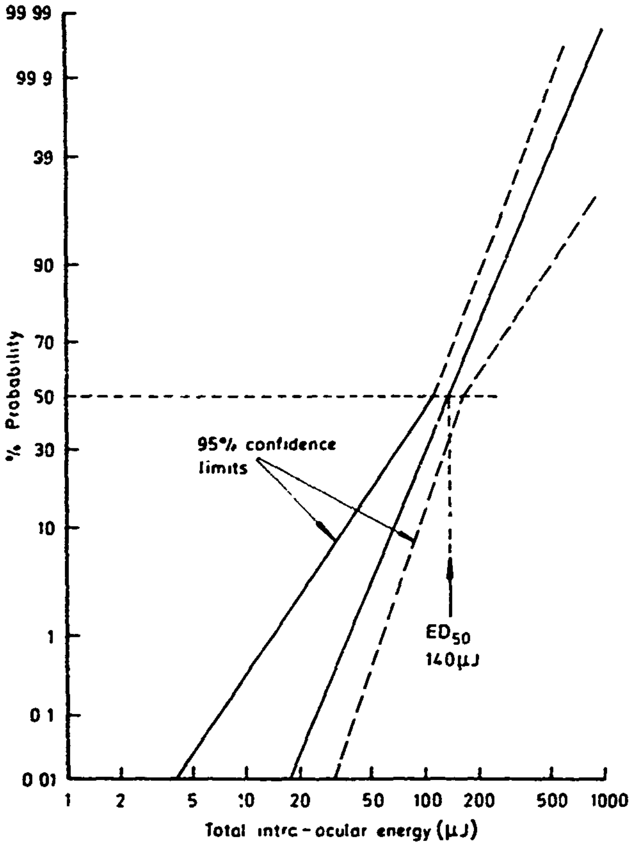

Fig. 3
Ophthalmoscopic retinal threshold damage probabilities
(Q-switched neodymium laser. 30 micron image diameter).

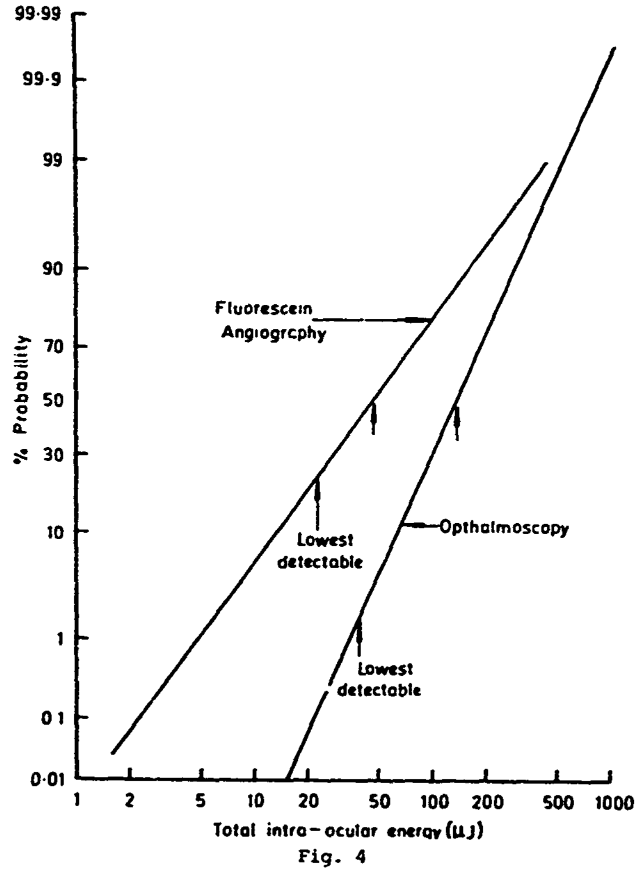

Fig. 4
Comparison of fluorescein angiography and
ophthalmoscopy as methods of detecting retinal damage.

DERIVATION OF SAFETY CODES, I -- USA EXPERIENCE

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SUMMARY

The first laser exposure limits in the USA date back to 1963. At first only two or three limits were provided. However, since 1972, a sliding scale of limits varying with exposure duration, wavelength, and PRF have been in use and are now standardized throughout the USA. The problems encountered in evolving these limits and the complementary laser system classification and field safety controls will be presented.

1. INTRODUCTION. Although the first safety codes for lasers date back to 1965, it was not until 1968 that the first detailed code of practice was published in the USA.[1] This document, "A Guide for Uniform Codes or Regulations for Laser Installations ", was developed by the American Conference of Governmental Industrial Hygienists[2] and for the most part was an adaptation of the first draft of the US Army Technical Bulletin, TB MED 279.[3] The exposure limits in this guide were first given widespread publicity when they were recommended by the first International Laser Safety Conference which was held in Cincinnati, Ohio in 1968. These exposure limits were based on retinal burn studies with only a few lasers - principally the normal-pulse and q-switched ruby and neodymium lasers, and continuous white-light and argon-laser sources. For this reason the exposure limits were applied to only three exposure durations: 10 - 1000 ns, 1 µs - 0.1 s, and "CW". Different limits were then given for intrabeam viewing and for viewing extended sources. Thus, we had a set of six limits for visible and near-infrared lasers which could be adjusted slightly for different wavelengths based upon the relative absorption of the laser radiation in the retina.

2. THE OPTICAL GAIN OF THE EYE. At first we believed that different exposure limits should be applied for different pupil sizes.[4] However, in 1967 an article by R.W. Gubisch appeared in the Journal of the Optical Society of America which modified this approach.[5] This article showed that although more energy entered the pupil when it was dilated, much of this additional energy would serve to enlarge the effective image on the retina rather than add much to the retinal irradiance. This effect was later confirmed in some retinal burn studies performed by LTC Beatrice and his associates.[6] Therefore, in the Threshold Limit Values published by the American Conference of Governmental Industrial Hygienists (ACGIH) in 1969 and in the 1969 edition of the US Army's TB MED 279 on laser hazards, we provided only a single set of intrabeam exposure limits for all pupil sizes. We still permitted a higher exposure limit for daylight conditions when the pupil was constricted and when we were dealing with extended sources. Figure 1 shows the optical gain of the human eye for the intrabeam viewing of a laser with the relaxed normal eye. Notice that the optical gain varies very little with pupil sizes between 3-mm and 7-mm and is approximately 200,000. The peak irradiance in the retinal image is therefore largely unaffected by this variation in pupil size. We, therefore, conclude that the risk of injury from intrabeam viewing of a laser is essentially the same whether we view the laser at night with a 7-mm pupil or in daylight with a 3-mm pupil, if the retinal injury threshold is dependent only upon retinal irradiance and not upon image size. In 1968, my colleagues and I assumed that there was no dependence of retinal injury threshold with differing image size if the exposure duration was less than 0.1 ms, during which there would be insufficient time for the exposed retinal area to cool. It was well recognized at that time that the retina could withstand an irradiance of 1 $kW \cdot cm^{-2}$ for several seconds if the image was of the order of 10 µm to allow for cooling. At that time, many of us were inclined to believe that the apparent dependence of q-switched (20 ns) exposures upon retinal image size was an experimental artifact.[7-10] We now know that this dependence is real. Figure 2 shows that a spot-size dependence is observed for a wide variety of exposure durations. Figure 3 also demonstrates this dependence.

3. STEP FUNCTIONS. One of the chief complaints leveled at our simplified set of exposure limits was the presence of step functions. By this, I mean that the levels jumped a factor of ten at one point or another; for instance at 1 microsecond. At first this was no problem. But then lasers began to appear which had a pulse duration of 1 microsecond. Which level applied: The value of 10^{-7} $J \cdot cm^{-2}$ based on q-switched exposure data or 10^{-6} $J \cdot cm^{-2}$ based on normal-pulse data? This of course, was not the only problem. The CW laser exposure criteria of 1 - 10 $\mu W \cdot cm^{-2}$ did not allow for a momentary exposure but was based on the assumption of certain long-term effects. These ACGIH limits which were adopted by the US Army and US Navy were not adopted by the US Air Force. Scientists within the US Air Force felt the aforementioned spot-size dependence was real, and furthermore felt that no individual would continuously stare into a laser for more than a second. The US Air Force exposure limits[11] in 1969 were therefore much greater than the Army/Navy/ACGIH limits as is shown in Figure 3. Aside from the exposure limits for the eye, these standards recommended most of the same safety measures and medical surveillance. The skin exposure limits were the same. Since the Armed Services in the United States had sponsored most of the biologic research and accounted for much of the laser development in the USA during the 1960's, their standards were generally followed by industry to a large extent. But by 1969, it became clear that a national consensus standard on laser safety was desirable. The ACGIH standard, although national in scope, was developed and controlled by governmental industrial health personnel, such as myself, and industrial personnel could not play a role.

4. THE ANSI-Z136 STANDARD DEVELOPMENT. In 1969 an effort was initiated by the American National Standards Institute (ANSI) at the request of the US Department of Labor to develop a consensus standard for the "Safe Use of Lasers and Masers," later redefined as "Safe Use of Lasers-Standard Z136." The telephone group became the sponsoring activity, and Mr. George M. Wilkening of Bell Laboratories was designated chairman. When work got underway with subcommittees formed in 1969, the hope was expressed that a final standard could be completed in 1 year if all subcommittees worked diligently. The

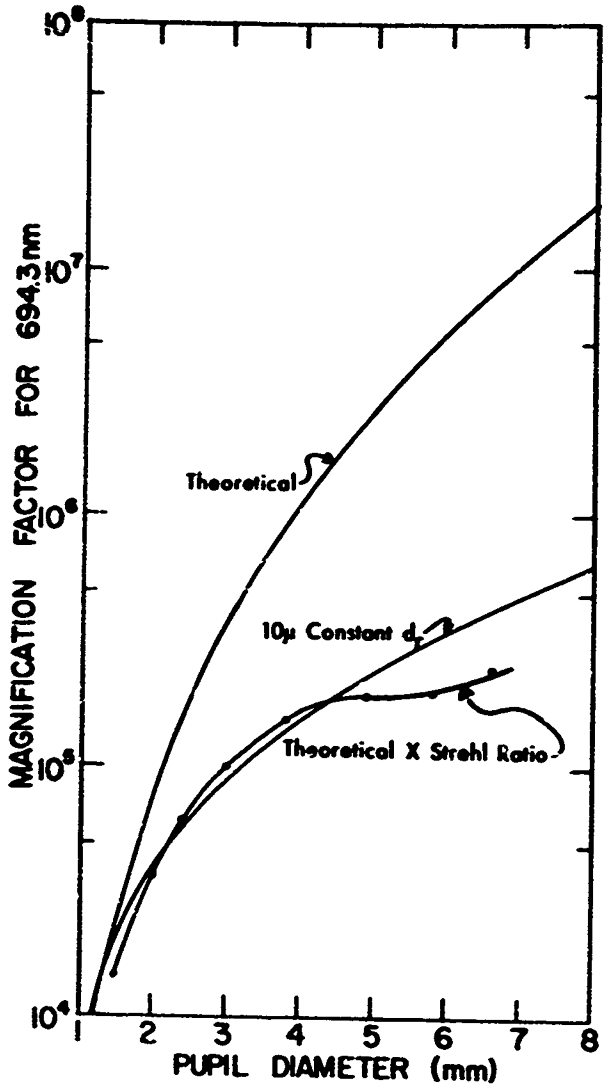

FIGURE 1. Influence of pupil size on the optical gain or magnification factor of corneal-to-retina irradiance for a point source viewed by the normal human eye. Theoretical curve was obtained using the Airy formula for peak retinal irradiance (Sliney, 1972). A second curve shows the optical gain for a constant retinal image diameter of 10 μ. The final curve is believed to more accurately represent the actual optical gain and was derived by multiplying the theoretical values by the Strehl ratios reported by Gubisch (1967). The Strehl ratios could be high (Sliney and Freasier, 1973).[21]

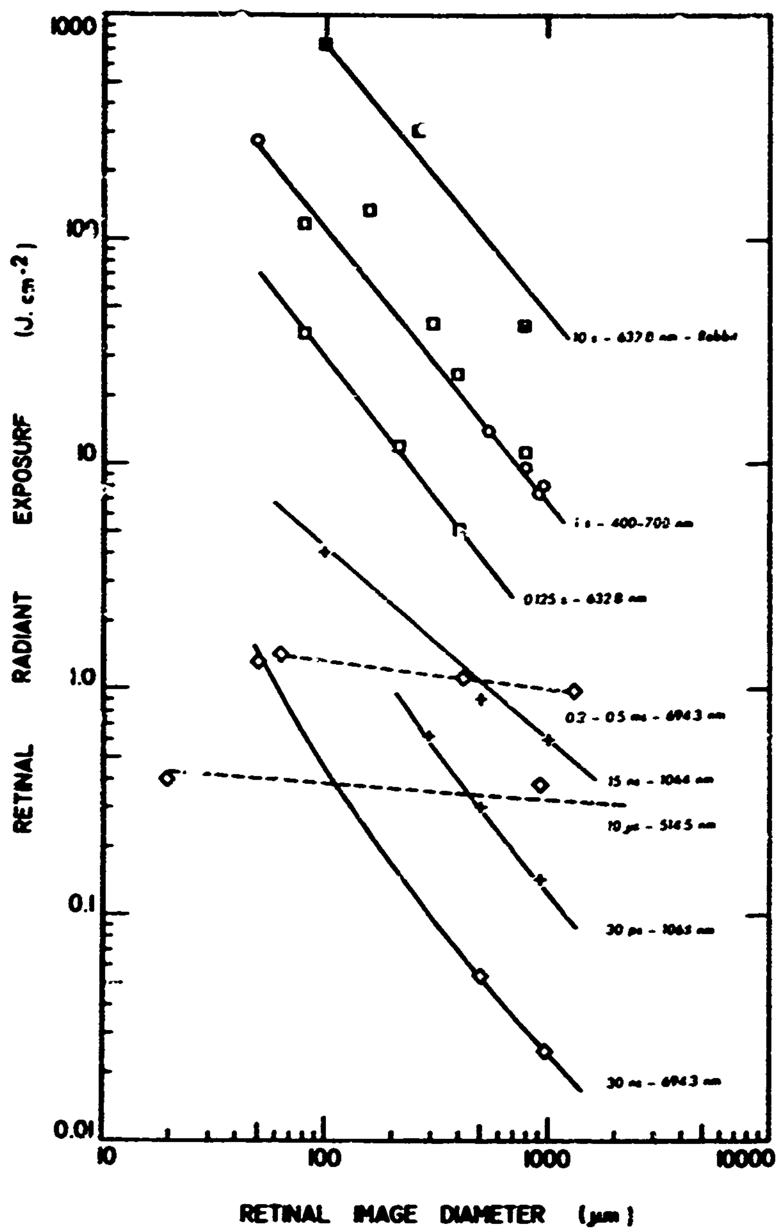

FIGURE 2. Variation of Retinal Burn Threshold in the Rhesus Monkey and Human Eye as a Function of Retinal Image Size.[1,6,17] Also for comparison, rabbit data for a 10 s exposure is shown.

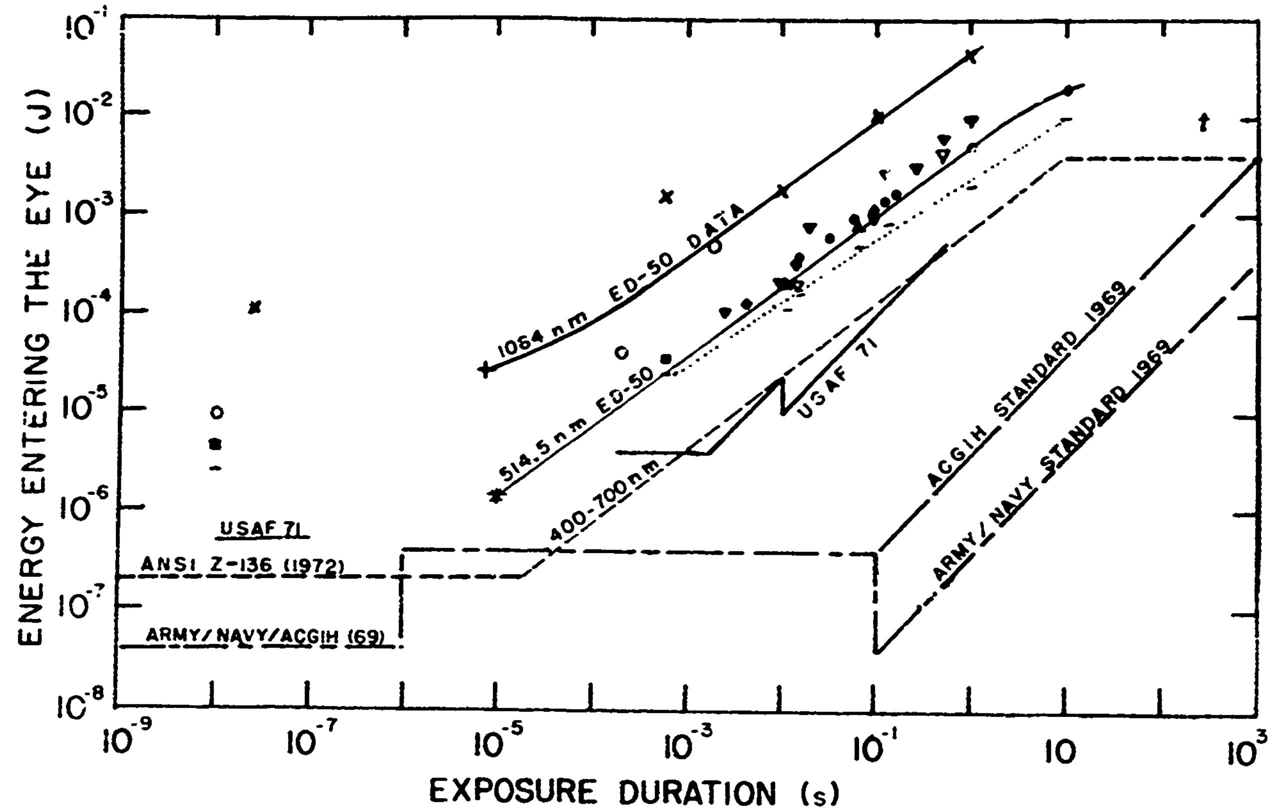

FIGURE 3. Selected data from many experiments which attempted to determine the laser retinal injury threshold in the rhesus monkey for the minimal image condition. Plotted for comparison are four protection standards applicable to intrabeam viewing (minimal image) condition. Biological data points represent ED_{50} values of Ham et al. (1970a) for HeNe (▼); Dunsky and Lappin (1971) for krypton (●). Bresnick et al. (1970) for argon (▲); Vassiliadis et al. (1971) for doubled neodymium, 530 nm [■, and for ruby (O)]; Vassiliadis et al. (1969) for argon, 514.5 nm (O); Lappin (1970) for He-Ne, 632.8 nm (▽), Naidoff and Sliney (1973) for welding are point source (†); Skeen et al. (1972a) for neodymium, 1064 nm (X); and Skeen et al. (1972b) for argon, 514.5 nm(*).[21]

experienced staff at the headquarters of ANSI in New York doubted that the standard could be prepared in less than 3 years. A general consensus was not achieved, however, until a committee vote on the last official draft, dated February 29, 1972. In May 1972, the ACGIH proposed a revision of their TLV's for laser radiation, which incorporated essentially all of the ANSI-Z136 Maximum Permissible Exposures (MPE's). The ANSI standard was quite complex and because most of the ballots on the February 29th draft indicated a desire for editorial changes for clarity, the final draft was considerably revised and was issued on November 23, 1972 as a final draft for submission to the ANSI Board of Standards Review. The document was approved on April 26, 1973 and was issued in October 1973.[12] The military services, and other Federal and state agencies that make use of laser protection standards, adopted most of the new protection standards promulgated by ANSI and ACGIH.

5. FORMULATION OF LASER PROTECTION STANDARD EXPOSURE LIMITS.

a. The greatest departure in format made by the ANSI standard from previous standards is the lack of "step functions" to express the MPE levels. Previous protection standards all had values expressed as radiant exposure ($J \cdot cm^{-2}$) or irradiance ($W \cdot cm^{-2}$) for a specific range of pulse durations. With the advent of lasers having any pulse duration, it was necessary to provide a sliding scale without sudden "steps" at specific pulse durations. Indeed, such an approach permitted a closer approximation of actual biologic injury thresholds with safety factor added.

b. To establish a rationale for developing permissible exposure levels from biologic data required a careful analysis of the physical and biologic variables influencing the spread of the laboratory biologic data, the variables influencing the potential for injury in individuals exposed to laser radiation, the increase in severity of injury for supra-threshold exposure doses, and the reversibility of injury. Additionally, the accuracy of instruments available for radiometric measurements and the desire for simplicity in expressing the levels have influenced the protection standard levels.

c. It was difficult to properly weight these many factors. Interestingly enough, I took a poll of several specialists who had involved in the development of the protection standard levels showing that although almost all of the specialists agreed to a certain set of MPE's or TLV's, they had a wide range of different rationales.

d. There was never any serious discussion of having separate military and civilian protection standards, since it was always agreed that a threshold of injury existed. No benefit-vs-risk analysis applied to the setting of the standard values. Benefit vs risk analysis was to be applied in the field evaluation of lasers.

6. LASER HAZARD CLASSIFICATION AND CONTROL MEASURES.

a. The ANSI-Z136 standard contains a well-developed and formalized scheme of classifying lasers based upon the laser's degree of hazard. This scheme evolved from previous standards and guidelines[13] and permits rapid hazard evaluation. Specific control measures and medical surveillance requirements vary depending upon classification.

b. In the final analysis, the specifications that define the hazard classes will be used more often than the protection standards (MPE's) themselves. Five classes are defined: Class 1 Exempt Lasers are those lasers incapable of producing a hazardous exposure condition; such lasers are unusual and generally limited to laser diodes. Class II Low Power Lasers are visible lasers (usually He-Ne) with an output power below 1 mW which are not hazardous unless an individual looks directly into the beam against his natural aversion response (i.e., longer than about 0.25 sec). Class III Medium Power Lasers require precautions to limit intrabeam viewing of the direct beam or a specularly reflected beam. The laser does not present a fire hazard, a skin hazard, or diffuse reflection hazard. In contrast, a Class IV High Power Laser does present a fire and skin hazard and/or a diffuse-reflection hazard, and very stringent control measures are required. Class V Enclosed Lasers, as the name implies, are those within an interlocked enclosure such that emitted laser radiation from the enclosure is not hazardous.

7. A SUMMARY OF THE ANSI AND ACGIH EXPOSURE LIMITS. In this brief lecture I cannot go into much detail about all of the exposure limits given in Tables I-IV. These protection standards are intended for exposure to laser radiation under conditions to which nearly all personnel may be exposed without adverse effects. The values were intended to be used as guides in the control of exposures and should not be regarded as fine lines between safe and dangerous levels. They are based on the best available information from experimental studies performed up to 1972.

8. LIMITING APERTURES.

a. One of the problems in developing exposure limits for any standard is the specification of the limiting aperture over which the level must be measured or calculated. For the skin, where no focusing takes place, one would like to have as small an aperture as possible. Unfortunately, the smaller the aperture, the more sensitive an instrument must be, the greater the inaccuracy will be due to calibration problems and the more difficult the calculations may be. We felt that a 1-mm aperture was about the smallest practical size to consider. For continuous exposure conditions, heat flow and scattering in the skin would tend to eliminate any adverse effects or "hot spots" which were smaller than 1-mm. The same arguments hold for exposure of the cornea and conjunctiva to infrared radiation of wavelengths greater than 1.4 µm. Furthermore, atmospherically induced "hotspots" and mode structure in multimode lasers seldom account for localized beam irradiances which are limited to areas less than 1-mm in diameter. Another problem appears at wavelengths greater than 0.1 mm. At these far-infrared wavelengths the aperture size of 1-mm begins to create significant diffraction effects and calibration becomes a problem. However, "hotspots" must, by arguments of physical optics, be generally larger than at shorter wavelengths. For this reason we chose a 1-cm or 11-mm (which has a 1 cm^2 area) aperture for wavelengths greater than 0.1 mm.

b. In the retinal hazard region of the spectrum, which extends from approximately 400 nm to 1400 nm, the aperture over which the incident radiation can be averaged is the pupil of the eye, if the exposure limits refer to the eye. A pupil size of 7-mm was finally decided upon, although not without a great deal of debate. I am sorry to report that the 7-mm aperture was influence more by political than scientific considerations. If you recall, I pointed out earlier in Figure 1 that the optical gain of the eye was largely unaffected by pupil size. From this viewpoint a pupil size of 3 mm would appear more reasonable. Without going into detail I will simply say that certain laser products faired better if 1 milliwatt into a 7-mm aperture rather than 0.2 mW into a 3-mm aperture were chosen as the upper limit of Class II - Low Power Lasers. It is only fair to point out, however, that either approach lacks support from actual retinal burn data. Because of the spot-size dependence of retinal injury thresholds , the 7-mm limit is not far from being the worst-case condition except for exposure durations of approximately a microsecond, where the spot size dependence of injury thresholds now appears to be the least. Some experts in the USA still maintain that a 5-mm aperture is really the worst-case condition.. In any case, the present exposure limits have a factor built into them which accounts for the expected variation of the worst-case aperture depending upon the exposure duration.

9. REPETITIVELY PULSED LASER EXPOSURE. The present exposure limits in the USA for repetitively pulsed lasers are based upon very limited data. I think that I can truthfully say that no one in our country has come up with a satisfactory explanation for the variation of the retinal injury threshold with cumulative exposures to short-pulses. By short-pulses in this regard, I mean pulse durations less than 0.1 ms. One would expect an additivity based upon the duration between exposures. Specifically if the pulse interval were less than 0.1 ms during which very little heat flow would take place, the exposures should add very nicely. They do not. Furthermore, if the pulses are separated by a period of time sufficient for the temperature to decrease to ambient, an additive effect is still noted for q-switchd pulses. Until the additive mechanism is understood the present exposure limits must be treated with great care. Figure 4 shows the correction factor that applies to pulse trains where each pulse lasts for less than 10 µm.

TABLE I. **Protection Standards for Typical Lasers**

Type of laser	PRF	Wavelength	Exposure duration	Protection standard for intrabeam viewing by the eye
Single-pulse ruby laser	Single pulse	694.3 nm	1 nsec–18 µsec	5×10^{-7} J·cm^{-2}/pulse
Single-pulse neodymium	Single pulse	1060 nm	1 nsec–100 µsec	5×10^{-6} J·cm^{-2}/pulse
CW argon lasers	CW	488 nm, 514.5 nm	0.25 sec	2.5 mW·cm^{-2}
CW argon lasers	CW	488 nm, 514.5 nm	4–8 hr	1 µW·cm^{-2}
CW helium-neon lasers (for alignment, etc.)	CW	632.8 nm	0.25 sec	2.5 mW·cm^{-2}
			4–8 hrs	1 µW·cm^{-2}
Erbium laser	Single pulse	1540 nm	1 nsec–1 µsec	1 J·cm^{-2}/pulse
CW neodymium YAG laser	CW	1064 nm	100 sec–8 hr	0.5 mW·cm^{-2}
CW carbon-dioxide laser	CW	10.6 µm	10 sec–8 hr	0.1 W·cm^{-2}

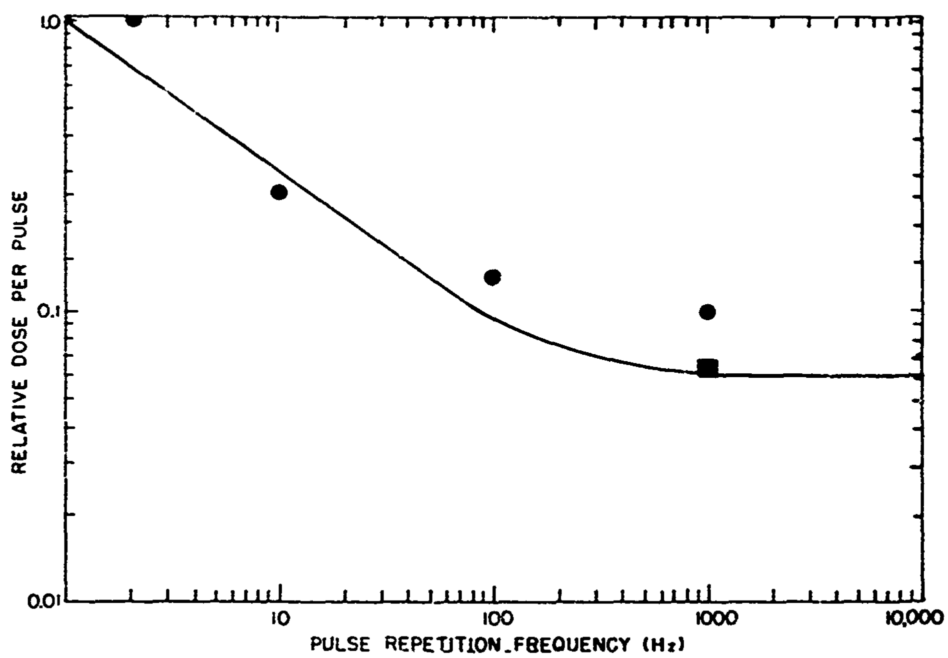

FIGURE 4. Correction factor (Cp) for repetively pulsed lasers having pulse durations less than 10^{-5} sec. The protection standard for a single pulse of the pulse train is multiplied by the above correction factor. Cp for a PRF greater than 1000 Hz is 0.06. Experimental data: ●, argon ■, neodymium. From Skeen et al. (1972).

10. THE "SAFETY FACTOR".

a. The margin we introduced to account for experimental error and errors in applying the exposure limits was very difficult to arrive at. To illustrate our problem consider the interpretation of one threshold point from a research study. This threshold is normally the result of considering a probit analysis of many data points.

b. Many laser retinal burn studies have tried to simulate the "worst-case" exposure from a safety standpoint, i.e., the relaxed normal eye exposed to a collimated beam - the minimal 10- to 20-μ retinal image. Consider the problems of determining the injury threshold for a 1-sec exposure of a minimal retinal image in a monkey from a CW visible laser. Obviously, measurement errors are introduced during the measurement of the laser power entering the eye and of the pulse shape. If the retinal injury threshold is strongly dependent on image size, a small error of ±0.25 diopter in refracting the monkey could result in a far-from-minimal image size of 35 - 45 μ. Likewise, such an error could be introduced if the monkey's accommodation drifted ±0.25 diopter while under cycloplegia. During a 1-sec exposure, even shallow breathing and blood circulation of the anesthetized monkey[14] would cause image wander significant in comparison to the image size. It is well known that the eyedrops used as a mydriatic and cycloplegic create a noticeable corneal haze in overdose, but what if lesser doses produce a corneal haze not readily evident to the experimenter? This introduction of additional scattering of the light could greatly reduce the laser power delivered to the central image, and a large percentage of the power could be delivered outside of the image unnoticed by the experimenter. Nonuniform retinal pigmentation and other anatomical factors will further spread the data.

c. If an experimenter made a great effort to place retinal lesions only at sites he judged to be of the same uniform pigmentation, one would expect a relatively steep ED CURVE to be the result. On the other hand, if he completely ignored this factor, the ED CURVE would have a shallower slope. Minimal retinal lesions placed in the vicinity of the optic disc could require an exposure dose 50-percent greater than that required for the same type of lesion in the center of the macula[15]. Still another parameter which may affect the retinal burn threshold, body temperature[16], is often overlooked and not controlled during experiments.

d. It is interesting, considering the source of errors, that occasionally an experimental data point probably does approach or even achieve the "worst-case." Figure 5 shows a hypothetical guess at the position and shape of the actual best-case, error-free experimental curve vs. a possible error-ridden experimental curve. It is therefore not at all surprising that the standard deviation for retinal injury thresholds for large retinal images (e.g., 500 μ) is far smaller, and hence the slopes of the probability curves are much steeper [17]. The more errors present, the less steep the slope of the curve. Hence if one chooses a sufficiently small probability ordinate point for a "safety" level, the standard writer is still safe.

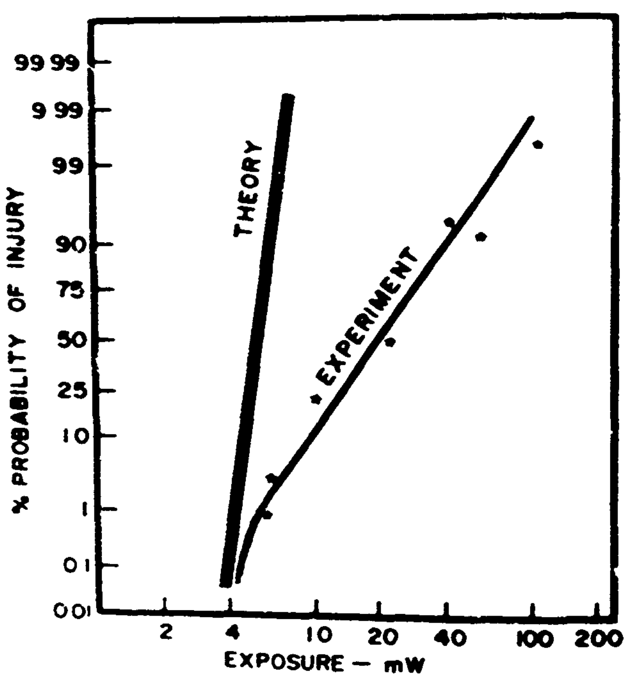

FIGURE 5. Hypothetical error-free experimental curve vs. an error-ridden curve for an experimental determination of laser retinal burn threshold for the minimal image size. Right-hand curve would represent data points where the minimal image size was seldom achieved.

11. SPECTRAL DEPENDENCE OF EXPOSURE LIMITS. Injury thresholds for both the cornea and the retina vary considerably with wavelength. We must consider how detailed we wish to track the actual injury threshold variation with wavelength. Normally the solution to these problems is a compromise: the protection standards are adjusted for different wavelengths but in a more simplistic manner than the actual biological data could permit. Figure 6 provides the product of the relative spectral transmittance of the ocular media and retina absorption, which is an indication of the relative spectral effectiveness of different wavelengths in causing retinal injury.[18, 19] However, these curves do not show the relative hazard to the lens of the eye in the near infrared. This is also plotted in Figure 6 for comparison with the spectral correction factor used in the ANSI-Z-136 standard.

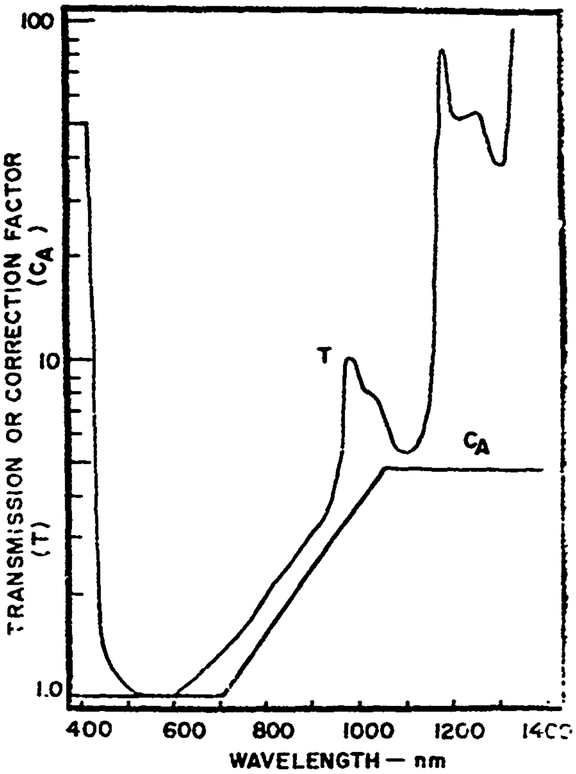

FIGURE 6. Normalized plot of reciprocal of the retinal absorption of optical radiation incident on the cornea based on the data of Geeraets and Berry (1968) and Boettner (1967). The relative spectral correction factor (C_A) used in the ANSI Z-136 standards is shown for comparison.

12. TYPES OF STANDARDS. Exposure criteria may be reflected in two general categories of standards: occupational health and safety standards and equipment performance standards. Within the US Government, occupational exposure standards are enforced by the Occupational Safety and Health Administration (OSHA) of the US Department of Labor. Federal product performance standards are enforced by the Bureau of Radiological Health (BRH) of the US Department of Health, Education, and Welfare. Federal standards for occupational exposure to nonionizing radiation have existed for microwave radiation and visible cw laser radiation since 1971. This year proposals for an ultraviolet radiation standard[4] and a laser radiation standard are under consideration within the Department of Labor. A proposed performance standard for laser products has been published in the Federal Register and could take effect as early as next year.

13. FUTURE OUTLOOK.

a. The principal protection standards for laser radiation are not likely to change for some time. However, the protection standards for repetitive exposures, long exposure durations (greater than a few minutes), and for wavelengths outside of the visible band (i.e., infrared and ultraviolet radiation) were based upon a considerable amount of extrapolation.[17] One can expect, therefore, that progress may be forthcoming in some of these areas of biologic research. Several groups are exploring the retinal injury thresholds for groups of short pulses.[18-20]. Little progress has been made recently in determing injury thresholds from ultraviolet and infrared laser radiation, with the notable exception of several US Air Force studies. One theory has been proposed for the action spectrum of UV-induced cataracts, but this is yet to be proven.[9] Preliminary data for retinal burn thresholds for 30-psec (picosecond) mode-locked

laser exposures obtained by Ham and co-workers showed that thresholds were reduced by a factor of at least 10 when compared with 30 ns (nanosecond) exposures to a minimal image area of the retina.[20]

b. Recent studies of long-term exposure of the retina to visible light have shown that we can probably increase the long-term exposure limits of laser wavelengths in the 500-900 nm spectral region. This conclusion is based on the action spectrum of the photic effect which manifests itself for exposures greater than 1 second.

14. FIELD MILITARY CONSIDERATIONS.

a. By contrast to industrial safety codes, military laser safety codes consider only one additional topic—field laser operations. The policy for use of tactical laser rangefinders and designators required several key decisions. The decision had to be made whether a "safe" viewing distance could be determined for a specific laser device. The questions on the effects of atmospheric scintillation on the beam and the effects of viewing optics influenced this decision. Finally, the question had to be answered whether absolute safety could be assured on any range if specularly reflecting surfaces were present. If absolutely safe operations were not possible, a certain acceptable risk-level would have to be established.

b. The safety implications of atmospheric scintillation of laser beams have long been recognized. With the testing of military lasers in the field, the "hotspots" created by atmospheric turbulence were looked upon as an uncertain variable in determining a laser's hazardous range[22]. In the past 10 years, several studies have been performed largely with the He-Ne lasers, in an effort to quantify this effect.[23-26] These studies resulted in statistical probabilities of finding an irradiance "hotspot" a certain factor above the mean. Deitz developed a nomogram (Figure 7) for such a purpose.[23] There has been some debate however, as to how useful such statistics are and whether they give the complete answer for safety analysis.

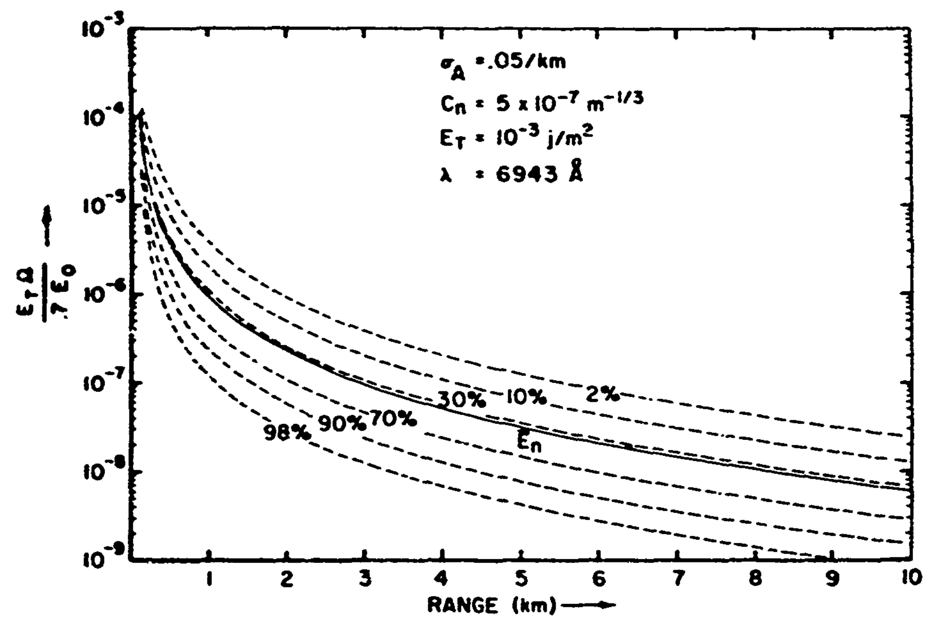

FIGURE 7. Eye safety nomograph of Dietz for C_n, the refractive index structure coefficient, typical of strong turbulence. The atmospheric attenuation coefficient, σ, is typical of very clear seeing conditions. The value E_T was the "safe" level of exposure and E_o was the output energy of the laser in joules. From reference 23 with permission of Applied Optics. The beam spread of the laser beam is expressed as a solid angle, Ω.

In numerous tests of field lasers by myself and my associates at the US Army Environmental Hygiene Agency over the past decade, we have found that the probability of occurrance of significant "hotspots" seems to be less than reported in the other studies. Our explanation has been that the other studies did not take into account the beam spreading which is always present during periods of strong turbulence. This spreading of the beam reduces the average beam irradiance such that the excursions of localized beam irradiance above the average are not as serious as they appear to be at first glance.[26 8]

c. Most studies were performed by atmospheric physicists who were looking only at the irradiance profile of the laser beam, i.e., the beam "cross section". They did not look at the projected radiance of the laser. The latter parameter is, however, of significance from an eye-safety standpoint. The radiance or "brightness" of an extended light source determines the irradiance falling on the retina.[27] However, the parallel rays of a point source, are always imaged on the retina as a minimal image. A source such as a laser is effectively a point source when the intrinsic divergence of the light rays entering the pupil is less than 0.3 mrad. When "turbulons" in the atmosphere tend to focus the collimated rays in a laser beam, the focused rays can have a divergence greater than 0.3 mrad and the resulting retinal image is increased. The safety question that must be answered where the eye is located in a "hot spot" is whether the retinal irradiance will be increased over that occurring during quiet atmospheric conditions.

d. For an extended source we can apply The Law of Conservation of Radiance. A glass lens (or a turbulon) or a telescope cannot increase the source raiance, and therefore cannot increase the retinal irradiance of a searchlight or other light source that is already resolved by the eye. If, however, the source cannot be resolved by the unaided eye or by a telescope, then a turbulon can increase the apparent brightness of the laser. At the US Army Environmental Hygiene Agency we conducted an evaluation of photographic images of a laser over several atmospheric path lengths. This effect on the extended image of more-or-less constant irradiance is shown in the photographs of Figure 8. Using a beam splitter and irradiance monitor in front of the camera, we were able to correlate beam irradiance with each image. The microdensitometer scans also permitted a careful analysis of the irradiance profile on the film.

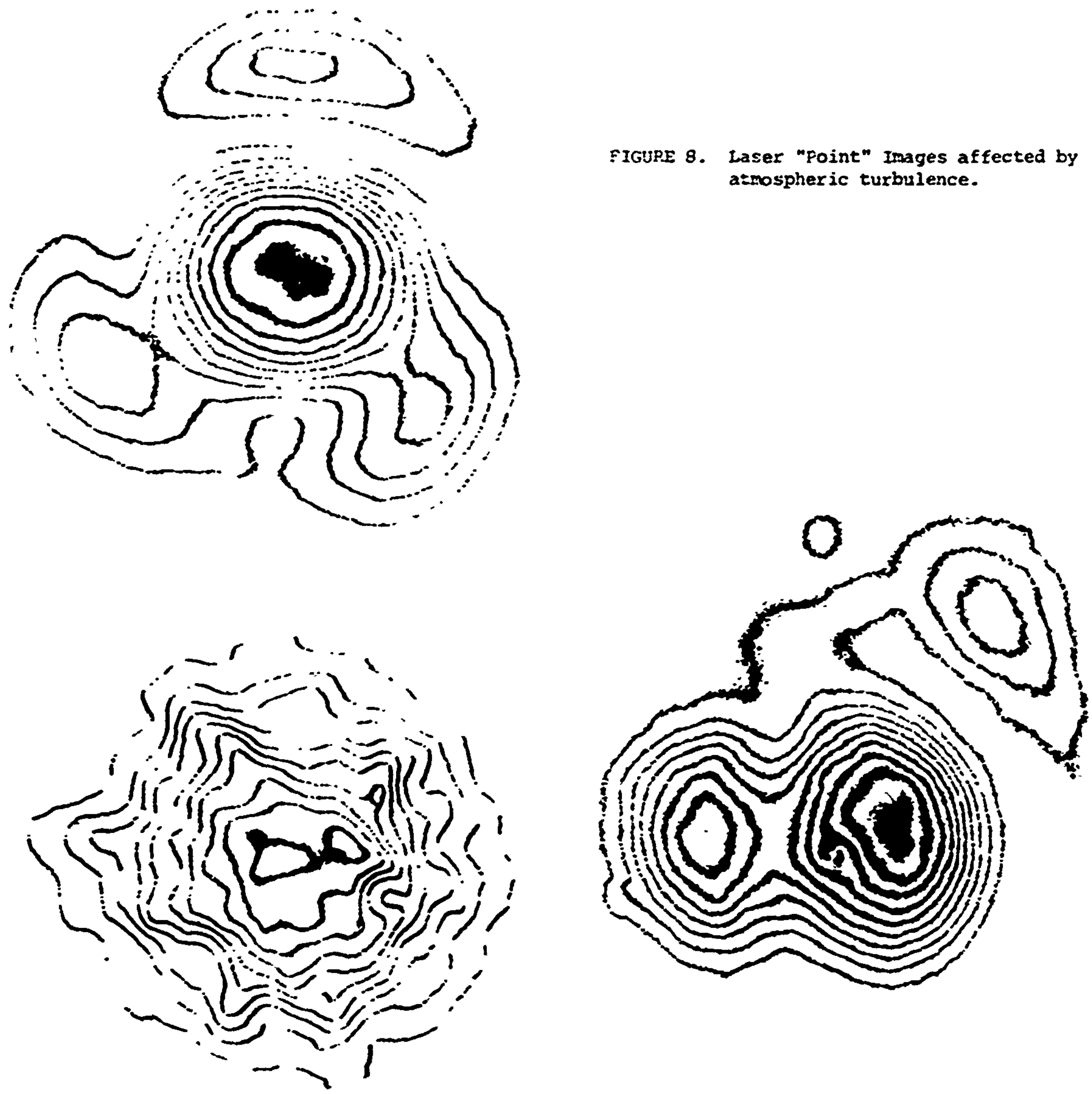

FIGURE 8. Laser "Point" Images affected by atmospheric turbulence.

e. Based on such experiments we now feel that turbulence does not so significantly add to the laser hazard as was believed in the past. But there is another factor that has not yet been mentioned. So far we have tacitly assumed that laser-induced retinal injury is only dependent upon retinal irradiance. This is not the case for many CW or short-pulse laser exposures; the injury threshold irradiance decreases for increasing image size.[6 18] This greatly complicates the determination of the increased retinal hazard due to scintillations. The exposure from a CW laser of course becomes averaged over a number of scintallations, and we disregard scintillation for these lasers.

f. When we finally add all of the probabilities we realize the small chance of an accident. Consider first, that an individual is looking into a pulsed laser; second, that his eye is focused at infinity and his fovea directed at the laser; third, that his eye is within a significant hotspot; fourth, that the weather provides a good visual range; and furthermore, that his retina is more sensitive (more absorbing) than average; the chance is vanishingly small. The added risk of someone being within the beam with a telescope or binocular is probably greater. For this reason we normally insist in the US Army that the beam be terminated by a backstop such as a hill within a controlled area[29] unless it is pointed skyward. Fortunately people in aircraft being unable to stabilize a binocular do not use them and atmospheric turbulence is far less for a ground-to-air path. In the latter case, we calculate the hazardous range and we feel that it has meaning.

g. The control of specular reflections becomes the next remaining problem. Our approach has been to eliminate all flat surfaces of glass that may be exposed in the target area. If this is not possible, we try to operate in a clearing in the woods or in a valley, where no unprotected personnel can see the laser or the target. At first, this may sound very difficult to you, but I can assure you that we have never encountered a test or training exercise where we could not fullfil the safety restrictions.

h. The last major problem that one must face in establishing a safety program for military lasers is assuring that the beam is pointed into a controlled target area. This is largely a problem of beam alignment with the laser sighting telescope. Maintenance personnel must be aware of the importance of assuring this. On the range, a range safety officer must be sure that targets are not fired at within a certain buffer angle of 2-10 mils from occupied areas. We establish the buffer angle based upon tests of pointing accuracy of the beam and stability of the laser mount.

15. CONCLUSION. Although there is still much to be learned about the biologic effects of certain types of laser exposures, most of the present standards will probably remain intact for a considerable time to come. This year the ANSI Committee met again with the intention of modifying some of the long-term exposure limits, but no action has yet to be completed.

TABLE II. **Protection Standards for Ocular Exposure Intrabeam Viewing of a Laser Beam Single Exposure**[a]

Spectral region	Wavelength (nm)	Exposure time (t)	Protection standard	Defining aperture (mm)
UV-C	200–280	1 msec to 3 × 10⁴ sec	3 mJ·cm⁻²	1
UV-B	280–302	1 msec to 3 × 10⁴ sec	3 mJ·cm⁻²	1
	303	1 msec to 3 × 10⁴ sec	4 mJ·cm⁻²	1
	304	1 msec to 3 × 10⁴ sec	6 mJ·cm⁻²	1
	305	1 msec to 3 × 10⁴ sec	10 mJ·cm⁻²	1
	306	1 msec to 3 × 10⁴ sec	16 mJ·cm⁻²	1
	307	1 msec to 3 × 10⁴ sec	25 mJ·cm⁻²	1
	308	1 msec to 3 × 10⁴ sec	40 mJ·cm⁻²	1
	309	1 msec to 3 × 10⁴ sec	63 mJ·cm⁻²	1
	310	1 msec to 3 × 10⁴ sec	100 mJ·cm⁻²	1
	311	1 msec to 3 × 10⁴ sec	160 mJ·cm⁻²	1
	312	1 msec to 3 × 10⁴ sec	250 mJ·cm⁻²	1
	313	1 msec to 3 × 10⁴ sec	400 mJ·cm⁻²	1
	314	1 msec to 3 × 10⁴ sec	630 mJ·cm⁻²	1
	315	1 msec to 3 × 10⁴ sec	1.0 J·cm⁻²	1
UV-A	315–400	1 nsec–10 sec	$0.56\sqrt[4]{t}$ J·cm⁻² [b]	1
	315–400	10 sec–10³ sec	1.0 J·cm⁻²	1
	315–400	10³ to 3 × 10⁴ sec	1.0 mW·cm⁻²	1
Light	400–700	1 nsec–18 μsec	0.5 μJ·cm⁻²	7
	400–700	18 μsec–10 sec	$[1.8t/\sqrt[4]{t}]$ mJ·cm⁻² [b]	7
	400–700	10 sec–10⁴ sec	10 mJ·cm⁻²	7
	400–700	10⁴ to 3 × 10⁴ sec	1 μW·cm⁻²	7
IR-A	700–1060	1 nsec–18 μsec	$0.5C_A$ μJ·cm⁻²	7
	700–1060	18 μsec–10 sec	$[1.8t/\sqrt[4]{t}]C_A$ mJ·cm⁻² [b]	7
	700–1060	10 sec–100 sec	$10C_A$ mJ·cm⁻²	7
	1060–1400	1 nsec–100 μsec	5 μJ·cm⁻²	7
	1060–1400	100 μsec–10 sec	$[9t/\sqrt[4]{t}]$ mJ·cm⁻²	7
	1060–1400	10 sec–100 sec	50 mJ·cm⁻²	7
	700–800	100–[10⁴/C_B] sec	$10C_A$ mJ·cm⁻²	7
	700–800	[10⁴/C_B] to 3 × 10⁴ sec	$C_A \cdot C_B$ μW·cm⁻²	7
	800–1060	100 to 3 × 10⁴ sec	0.1 C_A mW·cm⁻²	7
	1060–1400	100 to 3 × 10⁴ sec	0.5 mW·cm⁻²	7
IR-B and -C	1400–10⁶	1–100 nsec	10 mJ·cm⁻²	1, 10[c]
	1400–10⁶	100 nsec–10 sec	$0.56\sqrt[4]{t}$ J·cm⁻² [b]	1, 10
	1400–10⁶	10 to 3 × 10⁴ sec	0.1 W·cm⁻²	1, 10

[a] C_A = (λ-700/224); C_B = (λ-699).
[b] These values are graphed in Figs. 12 and 17.
[c] 1 mm for 1400–10⁵ nm; 10 mm for 10⁵–10⁶ nm.

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TABLE III. Protection Standards for Skin Exposure to a Laser Beam

Spectral region	Wavelength	Exposure time (t) (sec)	Protection standard
UV	200–400 nm	10^{-3} to 3×10^{4}	(Same as Table II)
Light and IR-A	400–1400 nm	10^{-9} to 10^{-7}	2×10^{-2} J·cm^{-2}
Light and IR-A	400–1400 nm	10^{-7} to 10	$1.1 \sqrt[4]{t}$ J·cm^{-2} [a]
Light and IR-A	400–1400 nm	10 to 3×10^{4}	0.2 W·cm^{-2}
IR-B and -C	1.4 μm–1 mm	10^{-9} to 3×10^{4}	Same as Table II

TABLE IV. Protection Standards for Laser Radiation Exposure of the Eye Viewing Extended Sources and Diffuse Reflections 400–1400 nm

Wavelength nm	Exposure duration	Irradiance or radiant exposure on diffuse perfect surface	Radiance or integrated radiance from extended source
200–400	1 nsec to 3×10^{4} sec	(Use values in Table II)	
400–700	1 nsec–10 sec	$10\pi\sqrt[4]{t}$ J·cm^{-2} [b]	$10\sqrt[4]{t}$ J·cm^{-2}·sr^{-1}
	10–10^{4} sec	20π J·cm^{-2}	20 J·cm^{-2}·sr^{-1}
	10^{4} to 3×10^{4} sec	$2\pi \times 10^{-3}$ W·cm^{-2}	2×10^{-3} W·cm^{-2}·sr^{-1}
700–1060	1 nsec–10 sec	$10\pi C_A\sqrt[4]{t}$ J·cm^{-2} [b]	$10C_A\sqrt[4]{t}$ J·cm^{-2}·sr^{-1}
700–1060	10–100 sec	$20\pi C_A$ J·cm^{-2}	$20C_A$ J·cm^{-2}·sr^{-1}
700–800	100 to (10^{4} C_B) sec	$20\pi C_A$ J·cm^{-2}	$20C_A$ J·cm^{-2}·sr^{-1}
700–800	(10^{4} C_B) sec	$0.2\pi C_A C_B$ W·cm^{-2}	$0.2C_A C_B$ W·cm^{-2}·sr^{-1}
800–1060	100 to 3×10^{4} sec	$0.2C_A\pi$ W·cm^{-2}	$0.2C_A$ W·cm^{-2}·sr^{-1}
1060–1400	1 nsec–10 sec	$50\pi\sqrt[4]{t}$ J·cm^{-2} [b]	$50\sqrt[4]{t}$ J·cm^{-2}·sr^{-1}
1060–1400	10–100 sec	100π J·cm^{-2}	100 J·cm^{-2}·sr^{-1}
1060–1400	100 to 3×10^{4} sec	π W·cm^{-2}	1.0 W·cm^{-2}·sr^{-1}
1400–10^{6}	10 nsec to 3×10^{4} sec	(Use values in Table II)	

DERIVATION OF SAFETY CODES II - UK EXPERIENCE

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SUMMARY

The initial approach to laser safety by the United Kingdom was based on limited experimental data and so tended to be over-cautious, but recent studies, both in the UK and USA, have been related to the practical situation of ocular irradiation by parallel beams and has suggested that the retinal radiant exposure for damage increases with decreasing image size. This study suggested that a considerable relaxation of the British Standards Institute (BSI) recommendations published in 1972 was possible. The international use of laser equipment has emphasised the need for a unified approach and the United Kingdom evaluated the exposure levels recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) 1973 and incorporated in the American National Standards Institute (ANSI) Report Z 136. As a result the BSI has recommended the use of ACGIH exposure levels. Similar exposure levels are being adopted by many European countries, and have been recommended for use within NATO. It is hoped that it will be possible to update the ANSI recommendations on an international basis in the future.

A code of practice should be based not only on realistic exposure levels for damage, but on a system of classification which can identify lasers according to their hazard potential. For some military applications 'safe' viewing distances based on the present standards may prove operationally unworkable, and a more realistic approach to laser safety may be required.

INTRODUCTION

The history of Code of Practice and safe exposure levels within the United Kingdom can be divided into three main periods. The first code of practice for laser workers was published in 1965 by the then Ministry of Technology who at the time represented the largest single user of laser equipment in the United Kingdom. In 1968 the British Standards Institution issued a draft Code of Practice based on the earlier Ministry of Technology code which after modification and updating was issued as British Standard 4803: 1972 (Ref. 1). During this same period several other organisation and agencies published guides to their workers based on either their own interpretation of the limited research data available or on the early American laser safety guides, notably that published by the American Conference of Governmental Industrial Hygienists in 1968. In retrospect it is perhaps unfortunate that the British Standard code was being written during the period 1968-1970, for while being able to acknowledge the work of Vassiliadis et al (Ref. 2) we did not reflect the more recent work of this author and others which has subsequently led to the better definition of safe exposure levels. At the present time the British Standards Institution is revising its current Code of Practice to provide manufacturers of laser equipment with a set of standards and the users of laser equipment with recommended operating procedures and non hazardous exposure levels.

The early British Codes of Practice which were based on the limited experimental data tended to be somewhat over-cautious in their approach to laser safety. Table 1 summarises the maximum permissible exposure levels at the cornea given in BS 4803: 1972.

TABLE I

LASER TYPE	Energy density per pulse		Power density
	Q-switched 1 ns-1us pulsed p.r.f. 10 Hz	Long pulsed 1 us-0.1 s p.r.f. 10 Hz	Continuous wave long-term exposure
	J/cm^2	J/cm^2	W/cm^2
Ruby (0.69 um)	3×10^{-8}	1×10^{-6}	4×10^{-7}
Neodymium (1.06 um)	2×10^{-7}	3×10^{-6}	2×10^{-6}
Helium-neon (0.63 um)	-	-	3×10^{-7}
Argon (0.51 um) (0.48 um)	-	-	3×10^{-7}

As can be seen only three exposure durations are considered, 1 ns - 1 us, a range which includes the Q-switched laser pulses, 1 us - 0.1 second which covers the long pulse systems and 0.1 second upwards for

the continuous wave lasers. These values were applied to both the intra beam viewing case where the retinal image diameter of between 10 - 20 microns was limited by the ocular aberrations, and to the viewing of extended sources and diffuse reflections. However a second table (not shown here) gave the corresponding safe retinal exposure levels and several instances occurred of safety officers attempting to redefine corneal exposure levels for non-minimal retinal image sizes, without understanding the importance of image diameter on damage thresholds.

The more recent codes of practice ACGIH (Ref. 3) and ANSI (Ref. 4) have moved away from the concept of providing safe exposure levels for specific laser systems and have produced an overall 'blanket' code which covers the complete range of wavelengths and all possible exposure durations. While there is considerable experimental threshold data available at certain specific laser wavelengths and exposure durations where it is possible to make reasonably accurate estimates of the corresponding safe exposure levels, the 'blanket' type code by its very nature must still remain on the conservative side for the majority of possible laser parameters.

Current thinking on laser safety now places more emphasises on minimising the hazard rather than the accurate determination of safe exposure levels. The hazard potential from laser systems can be grouped into one of four main classes:-

Class I - lasers that are intrinsically safe: ie the maximum permitted exposure level cannot be exceeded under any conditions, or laser systems that are totally enclosed and by virtue of their engineering design cannot irradiate the eye or skin at levels in excess of the maximum permissible exposure levels.

Class II - are low power visible lasers either continuous wave or repetitive pulsed, which operate in the visible part of the spectrum between 400 and 700 nm that are not intrinsically safe but where eye protection is normally afforded by the blink reflex.

Class III - are those lasers which are safe only when viewed as an extended source at minimum viewing distance or whose output when viewed via a diffuse reflector cannot exceed the maximum permitted exposure level for diffuse viewing.

Class IV - are high powered laser devices which are capable of producing a hazardous reflection and must be treated with extreme caution.

This system of classification which is carried out by the manufacturer or supplier of a laser system allow the user to be able to identify the necessary hazard control procedures for safe operation.

Unfortunately most lasers of military importance will be classified as III or IV which means that they represent a direct hazard to the eye (or skin) and where by nature of the mode of operation the hazard could extend over several tens of kilometres. For instance a typical ruby laser range finder might have a Q-switched output of 100 millijoules with a beam divergence of 1 milliradian, using the safe exposure levels quoted in the draft STANAG 3606 of 5×10^{-7} joules cm^{-2}, the minimum safe viewing range can be calculated to be 5 kilometres, and represents the nominal distance from the laser at which the naked eye would not receive an exposure in excess of the recommended maximum exposure level. This nominal hazard distance may be modified by the use of optical viewing aids. Binoculars or weapon sites, unless fitted with absorbing filters will increase the energy entering the eye by a factor approximately equal to the square of the magnification of the device. Thus, the use of x10 binoculars would extend the nominal distance of the above system to 50 kilometres - an unacceptable range for most practical purposes.

The 'blanket' approach to laser safety while affording excellent protection to the majority of laser users and members of the public may not always be relevant to the military where in some roles a less cautious approach can be justified. Two possible solutions can be found to this problem. The first, which is outside the scope of this paper, is to define a hazard exposure level in terms of an acceptable overall probability of producing a loss of visual function. The second is to base safe exposure levels on a more accurate estimation of threshold damage combined with realistic estimates of the eye's optical properties. The studies relating to the hazard from the Q-switched neodymium laser affords an example of the second method. Fig. 1 shows a relationship between the estimated retinal image diameter in microns and the retinal radiant exposure in joules cm^{-2} for the ophthalmoscopic threshold (ED_{50}). As can be seen, the retinal radiant exposure increases with decreasing image size.

These variations of threshold Retinal Radiant Exposure (RRE) with image diameter had important implications in the determination of the safe exposure level for humans. For practical considerations it is necessary to express safe exposure levels in terms of the Corneal Radiant Exposure (CRE).

The regression equation derived from Fig. 1 is

$$\mathrm{Log}_{10} \underset{(J/cm^2)}{RRE} = 2.8149 - 1.0378 \ \mathrm{Log}_{10} \underset{microns}{dr}$$

$$\text{or} \quad RRE = 0.5029 \times d_r^{-1.0378} \quad (d_r \text{ in millimetres})$$

$$\therefore \quad CRE = 0.5029 \, d_r^{0.9622} \, d_p^{-2} \qquad \text{As } CRE = RRE \, \frac{d_r^2}{d_p^2}$$

In the majority of accidental exposures to laser radiation the incident energy can be considered as being perfectly collimated, resulting in a retinal image diameter that is limited only by the aberrations of the eye and the state of accommodation at the time of exposure. At the present time as there is insufficient accurate information on the modulation transfer function of the eye exposed to coherent monochromatic radiation and a simplified approach can be taken to establish a relationship between the various

optical parameters.

From geometric optics it can be shown that the retinal image diameter arising from a dioptric error ΔP_o is of the form.

$$d_L = d_p \frac{(q - L)}{L}$$ where q = distance from retina to refracting surface and L = new focal length is given by

$$L = \frac{1000\ (N_o - 1)\ N_L}{(P_o + \Delta P_o)\ (N_L - 1)}$$ (This term includes the dioptric error arising from a change in wavelength)

P_o is the dioptric power of the relaxed eye

N_o is the refractive index of transparent media at λ_o = 571.5 nm

N_L is the refractive index of transparent media at laser wavelength

A value for N_{1060} = 1.32578 has been calculated based on the information by Meyer et al (Ref. 5) based on the "water model eye".

A van Meeteren (Ref. 6) has shown how the observed increases in longitudinal spherical aberrations vary with pupil diameter. By replotting this information in a log form a mathematical relationship can be established:-

$$P_s = K\,d_p^{\,n}$$

and the resulting retinal image diameter will be given by

$$d_s = d_p \frac{q - L^1}{L^1} \quad \text{mm}$$

where

$$L^1 = \frac{1000\ (N_o - 1)\ N_L}{(P_o + \Delta P_o + \Delta P_s)\ (N_L - 1)} \quad \text{mm}$$

In this treatment both of the above aberrations arise from considerations of geometric optics and the larger retinal diameter is taken as the limiting value. However diffraction is always present, and the total effective retinal diameter is taken to be:-

$$d_r = \sqrt{d_d^{\,2} + d_o^{\,2}}$$ where d_o is the greater of d_L and d_s

and $$d_d = \frac{1.242\,\lambda_L\,q}{D_p N_L} = \frac{0.022736}{D} \quad \text{mm}$$

Values for CRE, based on the preceding assumptions have been computed over a range of pupil diameters and states of accommodation, and are presented in Fig. 2. The minimum threshold corneal radiant exposure of 4×10^{-4} J cm^{-2} is based on the experimentally determined total intraocular energy required to produce a 50% probability of causing an ophthalmoscopically visible lesion in the para macular of the rhesus monkey eye, and a factor of 20 should be included to exclude the possibility of damage at the electron microscopic level.

By comparison, it is of interest to note that if for a "near perfect" eye, if one assumes that independent of wavelength, a 7 mm diameter pupil will produce a retinal image 10 microns in diameter, then using the data in Fig. 1 the corresponding safe corneal exposure level can be calculated as:-

$$60 \times \frac{10}{7 \times 10^3} \times \frac{1}{20}$$

$$= 6.1 \times 10^{-6}\ \text{J cm}^{-2}$$

This is in close agreement with the current safe exposure level (ANSI) of 5×10^{-6} J cm^{-2} for Q-switched neodymium radiation.

Whichever safe exposure criteria is used, the nominal ocular hazard distance does not take into account the effects of the atmosphere on beam propagation. Middleton (Ref. 7) has shown how the effects of atmospheric attenuation can be computed from a knowledge of the wavelength and the daylight visual range (Fig. 3). For the ruby laser discussed earlier, the effect of atmospheric attenuation for a visual range of 20 Km, would be to reduce the hazard distance to 3.9 Km, or if x10 binoculars were used, to some 17 Km.

Small changes in the refractive index of the air due to variation of temperatures near ground level can increase the eye damage probabilities by the break up of the propagating laser beam. To a viewer this appears as scintillations (fluctuations in intensity). The hot spots or areas of localised beam intensification can have intensities that are 10 or 100 times the average beam intensity. At the present time there is insufficient data to allow an exact calculation to be made on the probability of hot spotting, however, the effect is more likely to occur on ground/ground or ground/air operations at shallow angles of incidence (less than 10 degrees) and are more likely to occur around dawn or dusk when there are uniform changes in

the atmospheric temperature. Additionally, hot spots are not likely to occur during overcast weather conditions, in rain or fog or when there is a wind of more than 10 knots. When conditions favourable to the production of hot spots, nominal hazard distances should be increased by a factor of 10, although this factor only applies to viewing by the unaided eye since large aperture optics tend to average out the hot spotting effects.

Within the next two or three years it is likely that international agreement will be reached on a system of laser classification. The present Safe Exposure Levels based on ANSI Z 136, which are designed to protect laser users and members of the public, are unlikely to be modified in the near future. In the United Kingdom, the British Standard 4803 (under revision) will form the basis for all military laser operations where non service personnel may be accidentally exposed.

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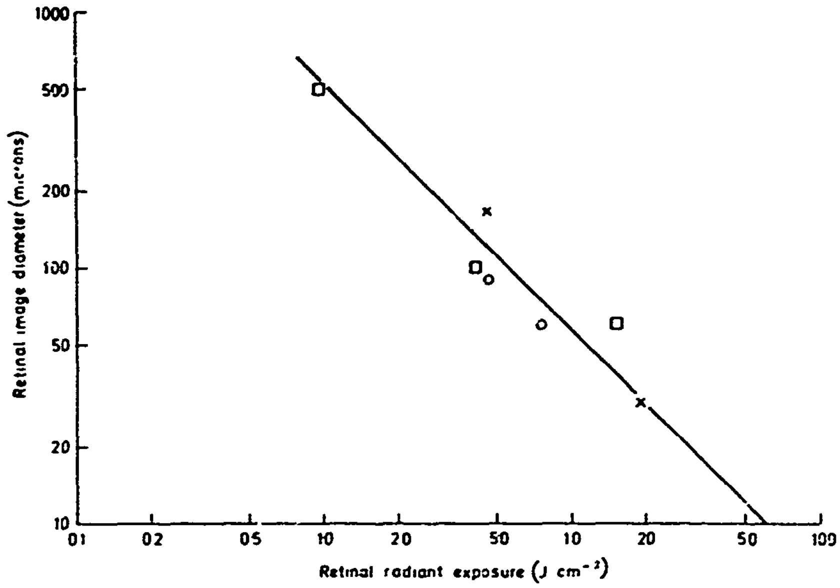

Fig. 1
The effect of retinal image diameter on the ophthalmoscopic threshold retinal radiant exposure.
Data from Ref. 7. Ref. 2. Borland et al (in preparation)

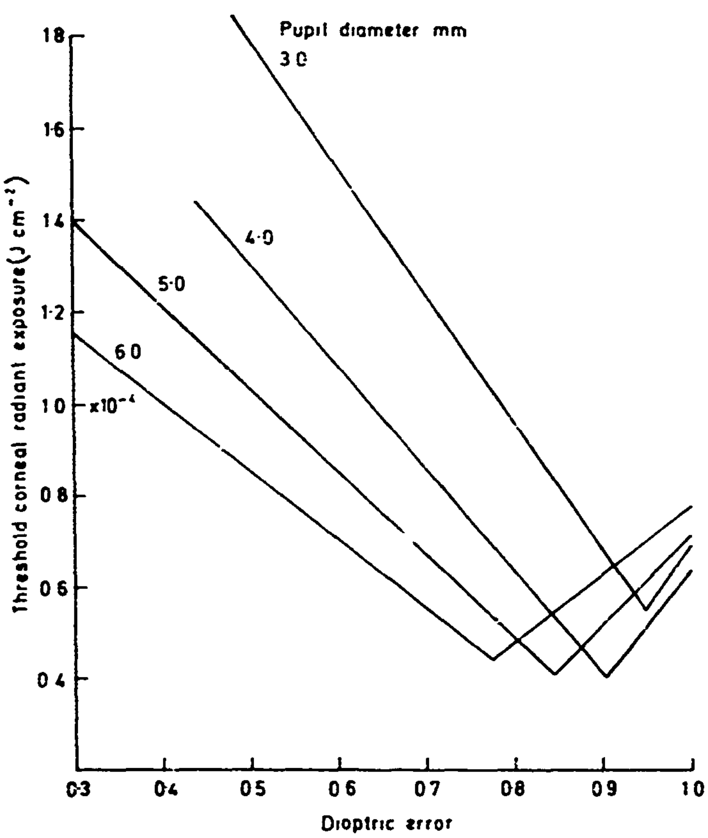

Fig. 2
Computed values of 'threshold' corneal radiant exposure versus dioptric error for Q-switched neodymium radiation.

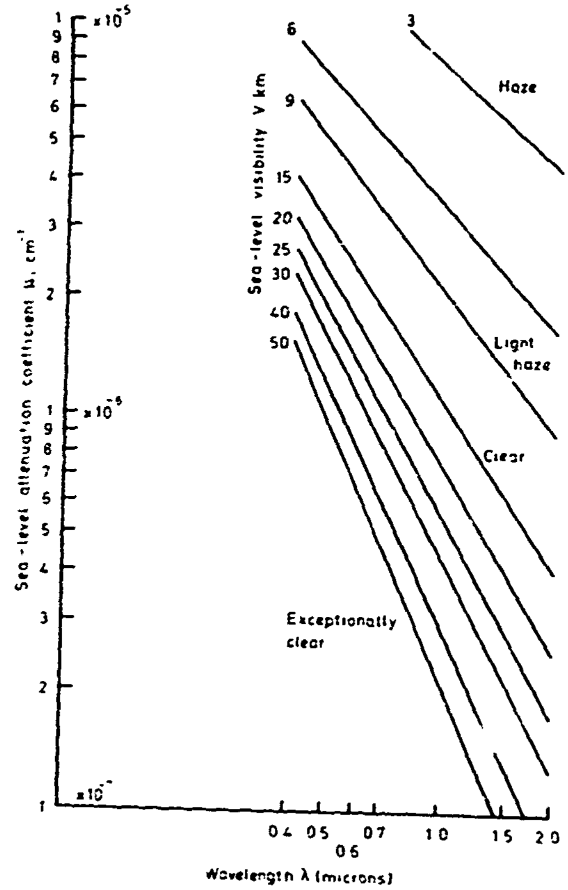

Fig. 3
Computed values of the atmospheric attenuation coefficient versus wavelength

$$u = 10^{-5}\left(\frac{3.91}{V}\right)\left(\frac{0.55}{\lambda}\right)^{Q}\ cm^{-1}$$

where $Q = 0.585\ V^{1/3}$
V = daylight visual range in Km
λ = wavelength in microns

OPHTHALMOLOGICAL EXAMINATION OF LASER WORKERS AND INVESTIGATION OF LASER ACCIDENTS

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SUMMARY

Though ocular surveillance of laser workers is indicated from medico-legal considerations, the clinical aspects are equally important. These include assessment of personnel with pre-existing ocular pathology, detection of possible chronic effects and confirmation of the effectiveness of the safety procedures. Such surveillance is costly and it is important to restrict screening to workers involved with lasers capable of causing ocular damage.

Those aspects of ocular structure and function which are relevant to laser induced damage in man are discussed. This includes the transmission and absorption characteristics of ocular tissues and the natural protective mechanisms of the eye. A scheme for the ocular surveillance of laser workers is presented with an evaluation of the role of field and other specialised examinations.

The procedure to be followed in the event of a laser accident is discussed. It is recommended that this involves a biophysical assessment of the accident scenario with particular reference to energy or power densities which may have been incident on the subject's cornea, as well as a detailed ocular examination of the worker. The clinical examination may include fluorescein angiography which has been found to be a more sensitive technique for detection of damage than ophthalmoscopy in monkeys.

INTRODUCTION

Lasers are potentially hazardous to the eye and may lead to damage which could be confused with other pathological changes. If such pathology is not discovered prior to access to a laser hazard area difficulties may arise in a medico-legal context and so the primary reason for ocular surveillance of laser workers tends to be of legal rather than medical importance. But there are other reasons, and these include the early detection of an inadequate safety regime, advising personnel with disease in one or both eyes, such as a recurring uveitis, of the dangers inherent in a laser environment and the possible detection of cumulative or long term effects of 'subthreshold' exposures to laser radiation. Though it may appear unsatisfactory that surveillance of laser personnel rests on legal rather than medical grounds, experience in this field emphasises that an environmental vision programme is expected not only by laser workers but also by industrial medical officers.

The main difficulties in establishing an ocular surveillance programme are cost and the small number of ophthalmologists with experience of laser induced pathology. This situation may be remedied by courses of instruction on lasers and their hazards. It is important to restrict surveillance to workers who are involved with lasers which can cause damage as defined in current codes of practice such as British Standards Institute 4803 (at present under revision) and American National Standards Institute Z 136. STANAG 3606 (1st Draft Edition No. 2) classifies laser systems hazards as follows:

a. Class I - Exempt. If the total output power or pulse energy concentrated into the limiting aperture, ie. 7 mm for 1.4 um or 1 mm for 1.4 um, which could occur during intrabeam viewing with a magnifying optical instrument, does not exceed the appropriate Protection Standard at the laser transmitter optics exit aperture, then the laser system is classified: Class I - Exempt. This implies a nominal ocular hazard distance of zero and thus no further hazard evaluation is needed on Class I systems. See, however, Class IIIa below.

b. Class II - Low Power. The following laser systems are classified: Class II - Low Power:-

(1) Visible (400 nm to 700 nm) CW laser devices with output power greater than 0.4 W but equal to or less than 1 mW.

(2) Visible repetitively pulsed laser devices which can emit a power exceeding the product of the appropriate intrabeam Protection Standard multiplied by the circular area of the limiting aperture (see para. a. above) for the maximum possible duration inherent in the system, but not exceeding that figure for a 0.25 s exposure.

No further hazard evaluation of Class II laser systems is required.

c. Class III - Medium Power. These are laser devices which emit radiation that is hazardous to view directly or after specular reflection, but not hazardous after reflection from a diffuse surface. The following laser systems should be classified: Class III - Medium Power:-

(1) Single-pulsed lasers of wavelengths between 400 nm and 1400 nm if the radiant exposure (H) per pulse at the transmitter optics exit aperture (= output energy (Q) per pulse/beam area) exceeds appropriate Protection Standard, but falls below the values for diffuse reflections.

(2) All CW lasers with power outputs greater than 1 mW but not exceeding 0.5W.

(3) For repetitively pulsed lasers of wavelengths between 400 nm and 1400 nm and of PRF greater than 1 Hz, it is necessary to determine both the CW and single pulse Protection Standards and then to apply the more stringent in evaluating the hazard. If the beam irradiance (E) or radiant

exposure (H) at the transmitter optics exit aperture exceeds the selected Protection Standard but falls below the limiting value for extended source viewing, then the laser system falls in this Class. A special Class IIIa is applied to laser devices which for intrabeam viewing with the unaided eye appear to conform to the criteria of Class I - Exempt, but where the Protection Standard is exceeded for viewing with magnifying optical instruments.

d. Class IV - High Power. These are laser systems which emit radiation that is hazardous even after reflection from a diffuse surface.

With this classification surveillance should be restricted to workers operating Class III and IV lasers. Personnel operating potentially hazardous lasers may be subdivided into those at high and those at low risk according to the nature of their duties. This division would not influence the type of examination but would modify the frequency of examination. But it may well be that those considered of low risk will be more careless or take more chances than those considered of high risk.

Tissues at Risk. In order to appreciate the manner in which laser radiation may affect the eyes it is of value to have an understanding of basic ocular structure and function.

The eyeball is roughly spherical and approximately 2.5 cm in diameter. It lies within the bony orbit suspended in fat. It is protected from damage in all directions except anteriorally where protection is limited to that provided by the lids. The eye rotates about its own centre in response to the pull of the extraocular muscles.

The globe consists of three coats which are modified at the front to admit light. The outermost coat or sclera is tough and supportive, the anterior transparent region is called the cornea. The middle coat or uvea is vascular and its prime function is nutritive. Anteriorally this coat becomes the ciliary body and iris whereas posteriorally it is known as the choroid. The innermost coat is neuroepithelial and called the retina, it is light sensitive and in extent corresponds to the choroid. The hollow globe is divided into two compartments, a small anterior chamber filled with a watery fluid called the aqueous, which is limited by the cornea and lens iris diaphragm and a larger posterior compartment which is filled with a clear jelly called the vitreous and is bounded by the lens iris diaphragm and the retina (Figs. I & II).

The anterior transparent window or cornea is approximately 1 mm thick at its junction with the sclera thinning to approximately .7 mm at its centre. It is composed of 4 layers, a thin outer epithelium which will regenerate if damaged, a thick layer of fibrous lamellae which is called the substantia propria and a thin inner elastic membrane called Descemet's membrane which is covered with an endothelial coat of single cell thickness and is continuous with the endothelium of the anterior surface of the iris. If damage is confined to the epithelium full recovery should take place within 48 hours but if the deeper structures are involved an opaque scar may result. The cornea in common with skin and conjunctiva is at risk primarily to lasers operating in the far-infra red above 1.4 microns, or in the near ultra violet below 400 nm. At these wavelengths all biological tissues are opaque (Fig. III). The cornea is transparent to wavelengths below 1.4 microns and above 400 nm and provides the majority of the refractive power of the eye having an approximate power of +43D.

The iris is a pigmented contractile tissue which has a hole in its centre called the pupil. The colour of the iris is a function of the degree of pigmentation, brown eyes being heavily pigmented, whilst blue eyes are only lightly pigmented. The pupillary diameter varies in size with the contraction of the iris musculature, the normal excursion being between 3 and 7 mm but with drugs this can increase to 1.5 - 8 mm. The pupil varies in size according to ambient lighting and regulates the amount of light entering the eye, this being proportional to the square of the pupillary diameter. This regulation will only apply to beam sizes greater than the pupillary diameter. The iris will absorb energy incident upon it, the degree of absorption being related to the degree of pigmentation. Lasers in the visible and near infra-red regions may cause iris damage (Fig. III).

The eye lens is the second refracting surface providing approximately +20D when unaccommodated with a power of accommodation which decreases with age being approximately +14D at 10 years, +4D at 40 years and +1D at 60 years. The lens continues the refraction started by the cornea and brings rays of light to a focus on the retina. The lens usually suffers damage by heat being conducted from the iris with which it lies in apposition although energy from some lasers may be absorbed directly in the lens substance.

As the refractive components of the eye form a roughly homocentric system, it is possible to regard the eye's focusing mechanism as being a single refracting surface. The reduced eye as proposed by Listing regards this surface as being 1.5 mm behind the cornea and having a radius of curvature of 5.7 mm. It lies between 2 media possessing refractive indices of 1 and 1.336 and its anterior and posterior focal lengths are 17.2 mm and 22.9 mm. With these figures it is possible to calculate the nature of images formed on the retina.

The retina is a thin transparent membrane which covers the posterior compartment except anteriorally and where it is perforated by the optic nerve. The outermost layer of the retina is the pigment epithelium and this lies on the choroid, inner to the pigment epithelium are the light sensitive receptors called rods and cones, inner to the rods and cones are the bipolar cells and their synaptic layers and innermost of all are the ganglion cells and their axons which converge on the optic disc (Fig. II). There is a specialised area of retina known as the macula with the foveal pit at its centre. This area lies approximately 3 mm temporal to the optic disc and is used for all tasks demanding high visual acuity both form and colour, and is an area composed entirely of cones. The rods which increase in density peripheral to the fovea, are used for night vision being highly light sensitive when adapted but they cannot differentiate colours or provide a good form acuity. If one considers foveal acuity as unity it is found that at 5^{o} eccentric from the fovea the acuity has dropped to 0.25, at 20^{o} eccentric to the fovea this figure has fallen to 0.05. It is damage to the macular region with which we are most concerned as it is cell damage here which causes the most profound effects on vision.

As can be seen from the retinal structure (Fig. II) light must pass through the nerve layers of the retina before reaching the light sensitive receptors; these rods and cones lie in intimate relationship with the pigment epithelium which envelops a portion of their outer segments. Energy from the visible and near infra-red lasers traverses the retina and is absorbed by the melanin in the pigment epithelium and choroid. This rapidly heats and by virtue of its intimate relationship with the receptors causes their damage. The extent of this damage will be dependent upon the energy reaching the pigment epithelium, the area irradiated and also on the degree of pigmentation present, which may vary racially.

As can be seen (Fig. III) there is a secondary absorbing site at the macula in the inner plexiform and nuclear layers where the blue/green wavelengths are selectively absorbed in the macula pigments. These blue/green wavelengths produced by the argon and dye lasers are also absorbed by the haemoglobin of red cells within the retinal vasculature.

To summarise, the eye is adapted to refract light in the wavelength band 400 nm - 1400 nm and the primary hazard from lasers operating in this region is to the pigmented structures within the eye. The pigment epithelium is the tissue most at risk and heat generated here may be conducted to the receptors giving rise to a scotoma or blind spot. The other pigmented tissues at risk are the choroid and iris. Heat may also be conducted from the iris to the lens, with which it lies in apposition, producing a cataract. The macular pigments and haemoglobin are secondary absorbing sites for the blue/green output of argon and dye lasers. The primary hazard from lasers operating outside the visible and near infra-red wavelengths is to cornea, skin and conjunctiva.

Natural Protective Mechanisms. The eye possesses protective mechanisms which may assist in limiting laser damage. Lacrimal fluid in common with biological tissue is opaque to the far infra-red wavelengths and to a limited extent the tear film will absorb and dissipate energy incident upon it. The cornea is richly innervated and any damage causes intense pain and triggers the sensory blink reflex within approximately .1 second, thereby limiting further damage. Bright light from visible lasers will stimulate the optical blink reflex but this is even slower than the corneal reflex and does not provide protection against pulsed lasers but it may be of value with continuous wave lasers. A bright working environment may help to protect the retina by ensuring that the amount of energy entering the eye is limited by a small pupillary diameter. Normal eye movements, tremors and microsaccades, whilst again too slow to mitigate damage from pulsed lasers may be of assistance with continuous wave and repetitive lasers by spreading the energy over a wider area. The optical quality of the human eye is such that spot sizes smaller than 10-20 microns are unlikely to be achieved and it is generally assumed that the maximum optical gain from cornea to retina is 4.5×10^5, approximately ½ million times.

Differential Diagnosis. The appearances of a laser burn may closely mimic a variety of normally occurring ocular pathologies. The list of diseases which may offer confusion with laser induced eye damage is legion and includes any condition which can cause areas of blanching, oedema or pigment clumping. A few examples will be cited. A retinal burn can resemble a focal choroiditis, a central serous retinopathy, an eclipse burn or a macular dystrophy. Lens damage can result in cataracts which may closely simulate those arising congenitally, from trauma or in senility. Burns of the iris can resemble an melanoma whilst a corneal burn in its later stages may produce a nebula which may be indistinguishable from those arising from ulceration or dystrophy.

Examination Protocol. It is important to ensure that the examination protocol for workers at risk, from hazardous lasers is both relevant and realistic. Given the diversity of wavelengths at which lasers can emit, all ocular tissues are potentially at risk.

The output of lasers which operate in the near ultra-violet and the far infra-red is absorbed by skin, conjunctiva and cornea. If a worker is solely involved with lasers emitting in these regions it is only necessary to examine the ocular adnexa and external surfaces of the globe with a loupe, particular attention being paid to a corneal examination using a slit lamp. The slit lamp comprises a low power microscope with a light source which is capable of producing an optical knife section. It is possible to focus at different depths and thereby examine in detail the transparent media and iris. The slit lamp techniques of retro reflection and specular reflection may also aid in demonstrating minimal damage which might otherwise remain undiscovered.

The examination scheme suggested for workers who are involved with lasers which may lead to intraocular as well as damage to the external surfaces, is necessarily more detailed. However all examinations should be reduced to the minimum and all hazardous or unpleasant procedures deleted where possible.

It is unlikely that a laser burn would increase intraocular pressure and so tonometry need not be included unless indicated. Similarly scleral indentation and examinations with a mirror contact lens and other examinations to visualise the retinal periphery are disliked and of doubtful value. Field examinations are time consuming and as scotomata produced by lasers are likely to be large and obvious or small, of around 10-30 microns, and difficult to detect, campimetry and perimetry have not been included as a routine. It has also been suggested that tests of ocular muscle balance should be undertaken but again it is most unlikely that lasers could cause any alteration in tropias or phorias, and the value of such tests is doubtful.

The examination proposed at Annex A attempts to assess the worker hazard both in terms of lasers used and his particular duties. There follows an enquiry into his ocular and general medical history, particular attention being paid to entoptic phenomena such as the development of after images, blind spots and alterations in vision both form and colour. The objective part of the examination is concerned with the external appearance of the eye and adnexa together with tests of pupillary function. This is followed by mydriasis which although inconvenient is considered necessary and a slit lamp examination of cornea, iris and lens and lastly an ophthalmoscopic examination of the fundus particular attention being devoted to the appearances of the posterior pole. Any pathology is documented, preferably photographically and in the normal eye a fundus photograph of the posterior pole including the optic disc and macula is considered desirable. Any further objective tests are left to the discretion of the examiner being based on his findings and opinions.

The subjective examination comprises tests of central and paracentral function, as it is burns of the macula affecting central function which would cause a significant disability. These include tests of visual acuity for near and far with a refraction where necessary. Colour vision is tested using the pseudo isochromatic plates or an approved lantern subtending a visual angle of 1 - 3°, as it is possible that coloured lasers might selectively damage one type of colour receptor when below burn threshold. Paracentral function is tested by means of the Amsler charts. The Amsler grid in its simplest form consists of a black card printed with a white grid pattern, this is held 30 cms from the subject's eye. The subject fixates a spot in the centre of the grid and at 30 cms the whole grid subtends a visual angle of approximately 10° around the fixation point. Each eye is tested in turn and the subject is asked six standard questions.

Question 1 - Do you see the white spot in the centre of the squared chart?

This question detects the presence of an absolute or relative central scotoma. If the subject only saw the fixation point when he looked off centre, it would reveal the presence of a foveal burn. This would be a severe disability.

Question 2 - Keeping the gaze fixed upon the white spot in the centre, can you see the four corners of the big square? Can you also see the four sides of the square? In other words, can you see the whole of the square?

This question does not have a great relevance in laser screening but could detect a scotoma coming in from the side such as the arcuate scotoma of chronic glaucoma, which might offer confusion.

Question 3 - While keeping the gaze fixed always on the central fixation point, do you see, in the whole square, the network intact? Or are there interruptions in the network of squares, like holes or spots? Is it blurred in any place? And if so, where?

This question reveals the presence of a paracentral scotoma absolute or relative anywhere, except the fovea, within the area of retina tested. It is the question of greatest value in laser screening.

Questions 4 and 5 - Always keeping the gaze fixed on the white spot in the centre do you see all the lines, both horizontal and vertical, quite straight and parallel? In other words, is every small square equal in size and perfectly regular?

Always fixing the gaze upon the centre point, independently of blurred spots and distortions, can you see anything else? A movement of certain lines? A vibration or wavering? Anything shining? A colour or tint? And if so, where on the square?

These questions reveal the presence of metamorphopsia and entoptic phenomena such as might be produced by small degrees of retinal oedema from heat or selective cone destruction by a coloured laser causing damage restricted to the photochemical level.

Question 6 - Keeping the central point fixed, at what distance from this point do you place the blur or distortion you see? How many small intact squares do you find between the blur or distortion and the central point that you are keeping your gaze upon?

This question accurately locates damage in relation to the fovea.

Great importance has been attached to the Amsler test as it is considered to be of great diagnostic value and rapid in use.

Fluorescein Angiography. Fluorescein angiography has proved to be a reliable and sensitive technique for the detection of laser damage to the retina. In animal studies using the rhesus monkey it has proved to be about 6 times more sensitive than ophthalmoscopy in the determination of the 50% probability of damage for the Q-switched neodymium laser (Ref. .. Brennan, D.H. (Fig. IV).

In man 3 cc of sodium fluorescein in a 20-25% solution are given by rapid intravenous injection and serial photography is commenced as soon as fluorescein illuminates the fundus and continued at appropriate intervals for up to ten minutes thereafter. The equipment in use at Farnborough comprises a Zeiss (West) fundus camera with a Baird Atomic B5 exciting filter and an Ilford 109 Delta chromatic 3 barrier filter in the motorised magazine. These filters allow only about 1% transmittance in the overlap zone of 480-500 nm. The film used is Ilford FP4 which is developed in Kodak D76.

The background fluorescence varies with phases of the vascular cycle. The first fluorescence seen is the choroidal flush when the dye first reaches the choroid. This fluorescence is patchy and irregular in distribution, it is followed by the arterial phase when the fluorescence assumes a fine granular pattern due to the dye in the choriocapillaris being viewed through discontinuities in the pigment epithelium. Fluorescence becomes maximal during the early venous phase and then commences to fade away assuming once more a granular pattern which becomes coarser with the passage of time. It is during the later venous phase that fluorescent laser lesions are most readily seen.

The ophthalmoscopic appearance of fluorescent lesions depends on whether they have been produced by a near threshold or supra threshold exposure. Threshold lesions fluoresce uniformly during the venous phase but lesions above threshold appear as a ring pattern during the early venous phase and fill slowly from the periphery toward centre during the late venous phase. Large fluorescent areas in excess of 75 microns are easily seen when superimposed on the background granularity but small lesions less than 75 microns are more difficult to see as they can be more easily confused with background grain.

In lesions at threshold levels the junction between adjacent pigment epithelial cells which are called zonular occludens become separated due to thermal damage and this opening represents a break in the chorio-

retinal barrier and permits free diffusion throughout the irradiated area and the lesion fluoresces uniformly. In lesions at above threshold level the pigment epithelium becomes coagulated and thus impermeable to fluorescein except at its periphery where the coagulated shrunken central plaque pulls open the junctions between normal and coagulated cells giving rise initially to the typical ring pattern. The ring slowly infills from the periphery to the centre with the passage of time.

Accident Procedure. In the event of a suspected laser accident the worker should be examined using the same protocol as detailed in Annex A. This examination should be conducted as soon as possible after the event preferably by the same ophthalmologist who carried out the original screening. In equivocal cases where damage cannot be excluded or where the extent of damage is difficult to assess fluorescein angiography is of great value provided this is done within 48 hours of the event.

When an accident is suspected the site of the incident should be 'frozen' until after a biophysical examination. This would attempt to determine whether the power or energy densities which had been present at the workers eye could have caused damage. This information could be of great value not only medicolegally but also in relating damage to energy levels and assisting in the development of new codes of practice.

REFERENCES

1. BRENNAN, D.H. Ocular examination of laser workers and investigation of accidents. Royal Society of Medicine, 66: p8-9, Sept. 1973.

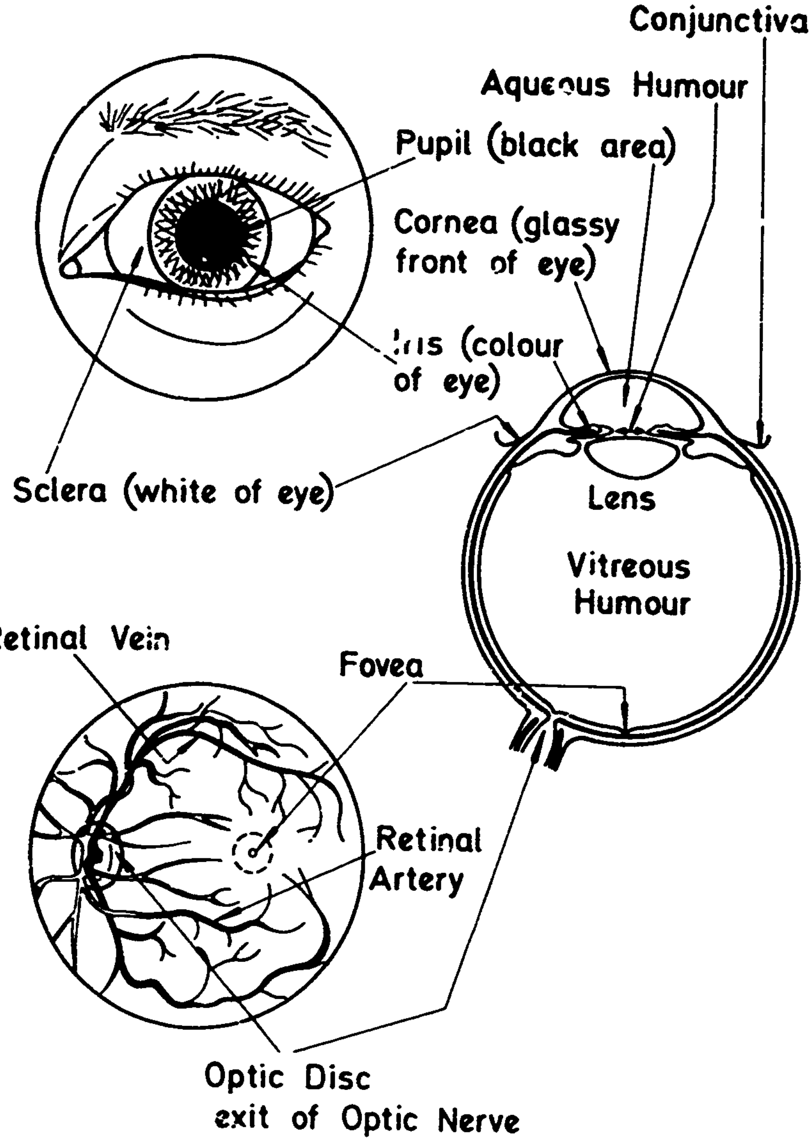
Conjunctiva
Aqueous Humour
Pupil (black area)
Cornea (glassy front of eye)
Iris (colour of eye)
Sclera (white of eye)
Lens
Vitreous Humour
Retinal Vein
Fovea
Retinal Artery
Optic Disc exit of Optic Nerve

Fig. I

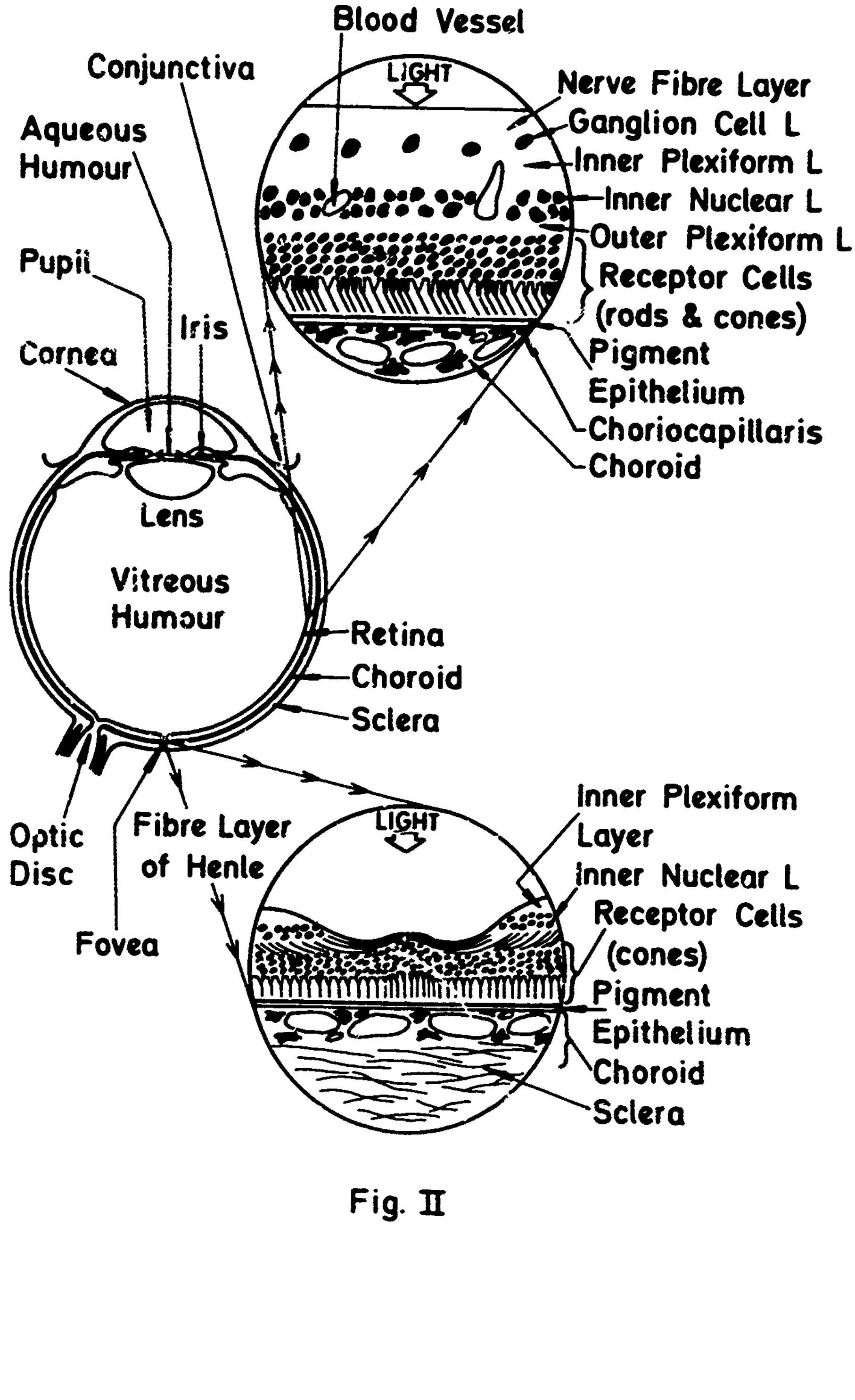
Blood Vessel
Conjunctiva
LIGHT
Nerve Fibre Layer
Ganglion Cell L
Inner Plexiform L
Inner Nuclear L
Outer Plexiform L
Receptor Cells (rods & cones)
Pigment Epithelium
Choriocapillaris
Choroid
Aqueous Humour
Pupil
Iris
Cornea
Lens
Vitreous Humour
Retina
Choroid
Sclera
Optic Disc
Fibre Layer of Henle
Fovea
LIGHT
Inner Plexiform Layer
Inner Nuclear L
Receptor Cells (cones)
Pigment Epithelium
Choroid
Sclera

Fig. II

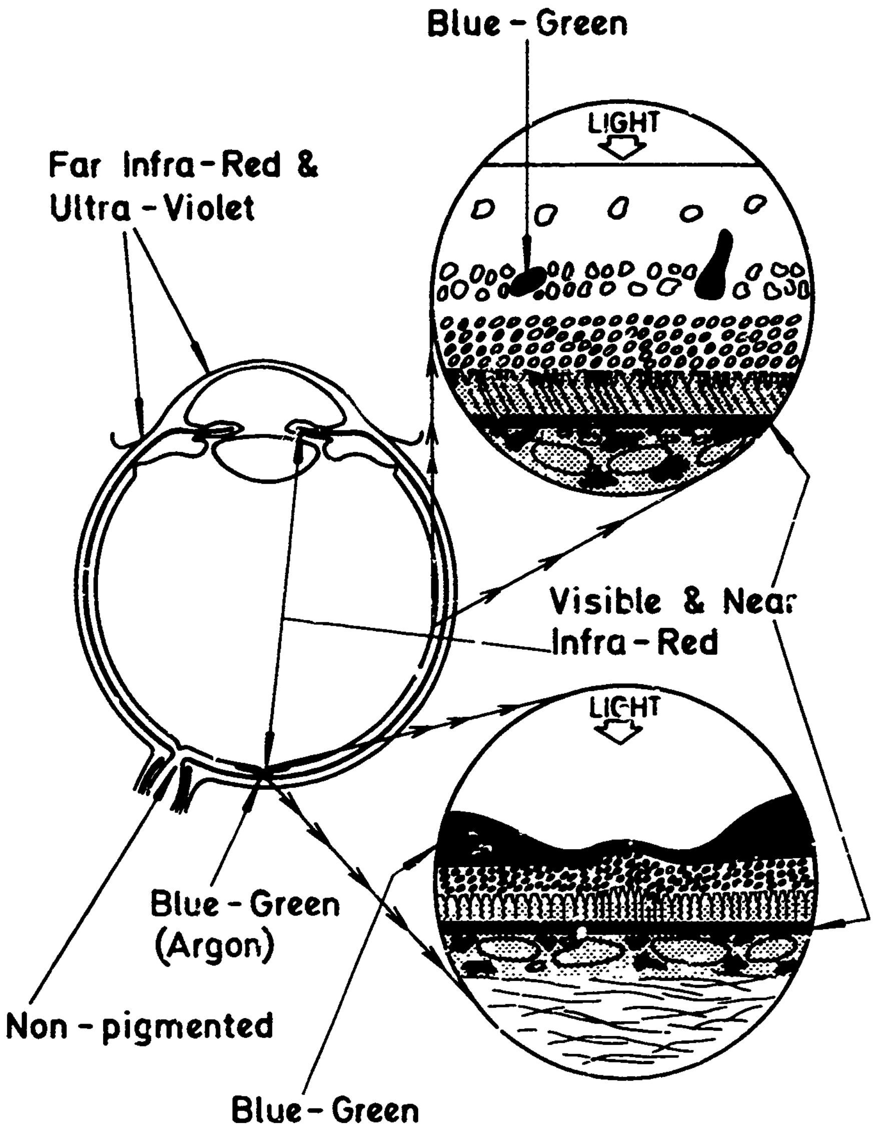
Blue - Green
LIGHT
Far Infra-Red &
Ultra - Violet
Visible & Near
Infra - Red
LIGHT
Blue - Green
(Argon)
Non - pigmented
Blue - Green

Fig. III

Fig. IV

Fluorescein angiogram of rhesus monkey retina
with fluorescent laser lesions between optic disc and macula

OPHTHALMIC SUPERVISION OF LASER WORKERS

Examination date ....Date of starting/ending laser work ....

Name .... Age ....

Address ....

Place of work ....

Laser Type *	Maximum Output	Class	Special Features
Worker Hazard Rating	High	Medium	Low
	Delete above where applicable		

Ocular history ....

....

....

....

Entoptic phenomena ....

....

Relevant general medical history ....

....

....

	Tick where applicable			
	Right		Left	
External Appearance:	Normal	Abnormal	Normal	Abnormal
1. Lids	......	....	......	....
2. Conjunctiva	......	....	......	....
3. Cornea	......	....	......	....
4. Sclera	......	....	......	....
5. Iris	......	....	......	....
6. Pupillary size	......	....	......	....
7. Pupillary reactions	......	....	......	....
	Far	Near	Far	Near
8. Visual acuity unaided	......	....	......	....
9. Visual acuity with correction	......	....	......	....
Correction prescription	....		....	
Refraction if V.A. achievable less than $^6/_6$ $^6/_6$		=6		=6/
	Normal	Abnormal	Normal	Abnormal
10. Amsler grid	......	....	......	....
Colour Vision:				
11. Lantern (1-3 minutes visual angle)	......	....	......	....
and/or				
12. Pseudo isochromatic plates				
	Accepted		Refused	
13. Mydriasis				

Slit Lamp:	Right		Left	
	Normal	Abnormal	Normal	Abnormal
14. Cornea	......	....	......	....
15. Iris	......	....	......	....
16. Lens	......	....	......	....
17. Fundus				
	Taken	Not Taken	Taken	Not Taken
18. Fundus photograph of posterior pole				

	Right			Left		
	High	Med	Low	High	Med	Low
19. Ocular pigmentation						

	Right	Left
Additional examinations at discretion of examiner, e.g. 20. Central fields 21. Applanation tonometry 22. 23. 24.		

Narrative description of any abnormalities discovered, accompanied by photographs or drawings where applicable.

Examiner's Name ....

Signature ....

* Workers who are restricted to the use of lasers operating solely in the infra red wavelengths, above 2 um e.g. carbon dioxide lasers, may have their examinations limited to the ocular adnexa and cornea.

LASER PROTECTIVE DEVICES

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SUMMARY

Since the eye is the most vulnerable site of injury for visible and near-infrared laser radiation, the primary interest in protective devices has centered on eye protection. The ideal characteristics of laser eye protection will be presented and the present filter materials and goggle designs will be compared with the ideal. Ultraviolet and far-infrared radiation can cause injury to the skin as well as to the eye at comparable exposure levels; hence the skin requires protection from lasers emitting in this region, although protection of the eye remains paramount.

1. INTRODUCTION.

a. Most industrially oriented laser safety codes emphasize the most desirable laser hazard control measure: the complete enclosure of the laser system. However, this is not always practical and is effectively impossible for military applications. Laser eye protection generally offers the best alternative to beam enclosure for military laser use in the field. For some laser maintenance procedures and for constantly changing experimental arrangements in the research laboratory, eye protection provides the simplest solution to the laser safety problem. Protection of the skin is seldom necessary and I will concentrate therefore, on eye protection.

b. Several factors play a role in determining whether eyewear is necessary and, if so, selecting the proper eyewear for a specific situation. At least three output parameters of the laser must be known (maximum exposure duration, wavelength, and output power/energy; or maximum exposure duration, wavelength, and output irradiance/radiant exposure). Additionally, knowledge of environmental factors such as ambient lighting and the nature of the laser operation is also required.

c. Laser eye protection generally consists of one filter plate, a stack of filter plates, or two filter lenses which selectively attenuate at specific laser wavelengths but transmit as much visible radiation as possible[1-8]. Eyewear is available in several designs--spectacles, cover-all types with opaque side-shields, and coverall types with somewhat transparent side-shields (Figure 1).

Figure 1. Laser Eye Protection Comes in Many Varieties.

2. APPLICATIONS.

a. In the indoor shop or laboratory environment, eye protection is required for unenclosed "high-power lasers" which are pulsed lasers which present a diffuse-reflection viewing hazard, or CW lasers having a total power above 0.5 W.

b. Several laser applications exist in which a potentially hazardous laser beam is propagated in the outdoor environment. Some construction applications, atmospheric research, and air pollution monitoring, as well as military applications fall into this category. In these applications, steps are taken at first to prevent individuals from entering the beam path or the laser from entering occupied areas, and eye protection is used as a last resort. Eye protection is extensively utilized where individuals must be "downrange" within the beam path as in some atmospheric laser beam propagation studies, laser communication experiments, and in two-sided tests of military laser rangefinders and designators.[9] If one were directing a laser at a specular target during a test or training exercise, eye protection for all within the hazardous envelope would be required (see Figure 2).

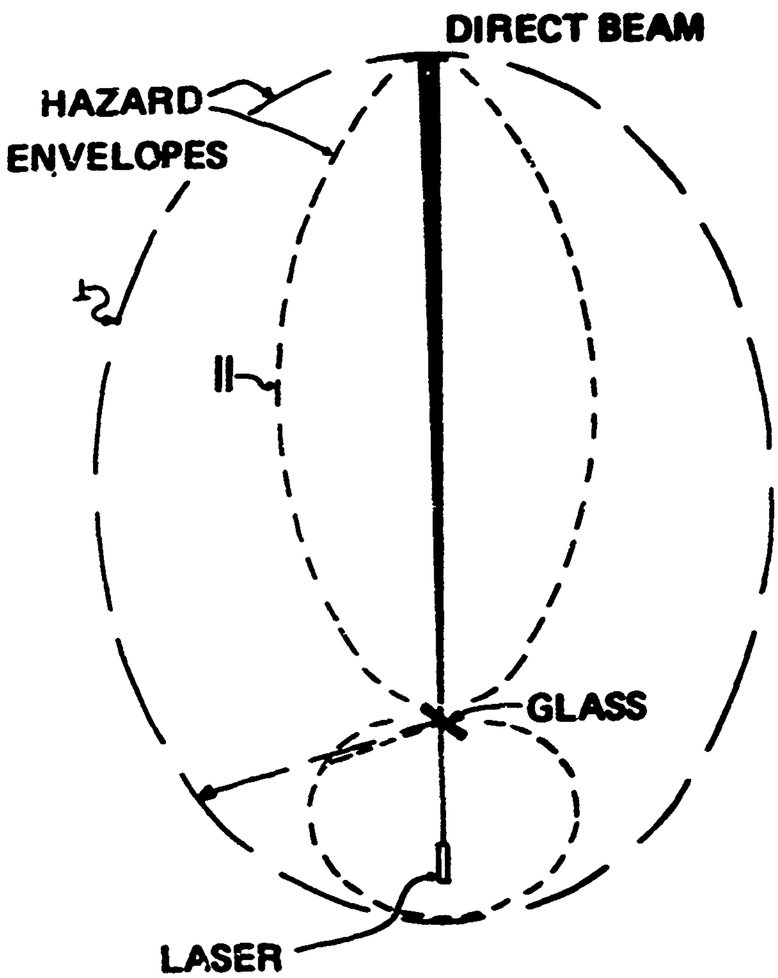

Figure 2. The Potentially Hazardous Specular Reflection Zones Depend Upon Laser Beam Polarization. If the Electric Vector of the Incident Light is Parellel(1) to the Plane of Incidence, then the Zones are Restricted.

c. Before deciding that laser protective eyewear offers the best solution for controlling potential hazards, one should consider alternative controls while being aware of the disadvantages of such eyewear. Most laser protective goggles are somewhat uncomfortable to wear for extended periods of time; lens surfaces fog in most environments; many goggles provide only "tunnel" vision, or at best, reduced peripheral vision; they reduce visibility; and they reduce total colour perception, as well as possibly rendering warning flares of certain colours non-visible. Reduced vision from eyewear can introduce increased risks in many occupations, for example to aircraft pilots. Moreover, an individual wearing eyewear in the vicinity of a laser beam path introduces an additional risk from specular reflections to any unprotected bystanders.

d. We have considered the risks of hazardous specular reflections from our own lasers in a combat environment. In our judgment, they are so small that we do not plan to provide eye protection for combat troops against this hazard, since the shortcommings of goggles outweigh this risk. On the other hand, with lasers directed at combat troops, there may be a sufficient risk to warrant goggles for troops in or near hard-point targets. Certainly in any test or training environment we require such eye protection. Considering nominal hazardous ranges and levels of ocular exposure at typical engagement distances leads us to this conclusion; the individuals at great risk are those viewing the laser source with optical instruments from within the beam. We now have protective filters built into the optical sights of some combat vehicles. These filters cna employ dichric coatings with much higher visible transmittances than could be used in individual safety spectacles.

3. LASER VIEWING ENHANCEMENT GOGGLES. Several commercial manufacturers have offered goggles designed to selectively transmit, rather than attenuate, at a specific laser wavelength. These goggles were designed for use with helium-neon lasers used in daylight in the constuction industry, to permit workers to readily locate the beam at much lower irradiances than would otherwise be possible. This type of goggle has not as yet found any use in the military environment. Obviously, if such goggles are on hand, the eyewear must be clearly marked that they <u>do not</u> offer eye protection.

4. PARAMETERS OF LASER EYE PROTECTION. Several physical parameters are useful in providing an adequate description for specific eyewear:

(a) Wavelength. The wavelength (s) of laser radiation limits the type of eyeshields to those which prevent the particular wavelength(s) from reaching the eye. It is emphasized that many lasers emit more than one wavelength and that each wavelength must be considered. Considering the wavelength corresponding to the greatest output intensity is not always adequate. For instance, a helium-neon laser may emit 100 mW at 632.8 nm and only 10 mW at 1150 nm nm, but safety goggles which absorb the 632.8 nm wavelength may absorb little or nothing at the 1150 wavelength. The only commonly encountered pulsed lasers which introduce this problem are frequency-doubled laser systems, such as Nd:YAG, which will have both 1064 nm and 532 nm emissions.

(b) Optical Density. Optical denisty is a parameter for specifying the attenuation afforded by a given thickness of any attenuating filter. Since laser beam irradiance may be a factor of a thousand or a million above safe exposure levels, <u>percent transmission</u> notation can be unwieldy. For instance, filters with a transmission of 0.000001 percent can be described as having an optical density of 8.0. Optical density D_λ is a logarithmic notation and is described by the following expression:

$$D_\lambda = \log_{10} \frac{E_o}{E} = -\log_{10} \tau_\lambda$$

where Eo is the irradiance of the incident beam and E is the irradiance of the transmitted beam of wavelength λ. Thus a filter attenuating a beam by a factor of 1,000 or 10^3 has an optical density of 3, and another filter attenuating a beam by 1,000,000 or 10^6 has an optical density of 6. The required optical density is determined by the maximum laser beam irradiance to which the individual could be exposed. The optical density of two highly absorbing filters when stacked is essentially the sum of two individual optical densities, but not exactly.

(c) The total transmittance of an absorbing optical filter is the product of the internal transmittance of the absorbing medium (which is dependent upon the filter thickness) and the transmission losses due to Fresnel reflection at the filter surfaces. Hence, two stacked filters bonded with optical cement will have slightly less density (~0.04) than if separated.

(d) The spectral transmittance of glass or plastic filter materials is generally obtained from a thin-filter sample which has been molded or ground to a useful thickness to provide no less than 1 percent transmittance within the wavelength band of interest using high quality spectrometer. The optical density for the material of a given thickness t_2 at a given wavelength may then be calculated from the transmittance τ, of the sample c[illegible]kness t_1 if the Fresnel reflection component is adequately accounted for 10. For a beam incident perp[illegible]ar to the filter surface, total transmittance τ is the product of the internal transmittance t_1 (dependent upon thickness) and the reflection loss R which itself is dependent only upon index of refraction.

$$\tau = R \cdot \tau_i = \frac{2n}{n^2+1} \cdot \tau_i$$

$$\text{The Density } D_i = -\log \tau_i = \log_{10} R - \log_{10} \tau \tag{3}$$

and

$$\frac{D_i \; (t_i)}{D_i \; (t_2)} = \frac{t_1}{t_2}$$

For example, if a 2-mm thick Schott® BG-18 filter[11] has a density due to internal attenuation of 1.96 (2.00 total density at 694.3 nm), then a 5-mm thick BG-18 filter would have a density of 9.8 due to internal attenuation, plus 0.04 due to reflection, hence 9.84 at 694.3 nm.

4.3 LASER BEAM IRRADIANCE OR RADIANT EXPOSURE. The maximum laser beam radiant exposure in Joules$\cdot$cm^{-2} for pulsed lasers or maximum laser beam irradiance in Watts$\cdot$cm^{-2} for continuous-wave lasers to which an individual may be exposed cannot always be readily determined. If the beam is never focused and is larger than the diameter of the eye's pupil, the output energy-per-unit-area (radiant exposure) or power-per-unit-area (irradiance) should be the guiding value. If the beam is focused or if the beam can be observed directly through binoculars, the maximum total beam energy or power output must be used.

5. VISUAL TRANSMITTANCE OF EYEWEAR. Since the object of laser protective eyewear is to filter out the laser wavelengths while transmitting as much of the visible light as possible, visible (or luminous) transmittance should be noted. A low visible transmittance creates problems of eye fatigue and may require an increase in ambient lighting in maintenance-shop or laboratory environments. However, adequate optical density at the laser wavelengths should not normally be sacrificed for improved visible transmittance. For nighttime viewing conditions, the effective visible transmittance will be different since the spectral response of the eye is different. Figure 3 shows the CIE "standard observer's scotopic (night vision) and photopic (day vision) responses of the eye according to the Commission Internationale de L'Eclairage[12]. These are mathematical functions that attempt to show the approximate spectral sensitivities of the eye for two types of human vision. They are probably the extremes of actual viewing conditions encountered with laser eye protection. Certain colored filters would therefore, affect daylight vision differently than night vision. Blue-green filter lenses such as BG-18, which are used to protect against ruby and neodymium lasers, therefore, have higher scotopic transmission values than red or orange lenses, and vice-versa.

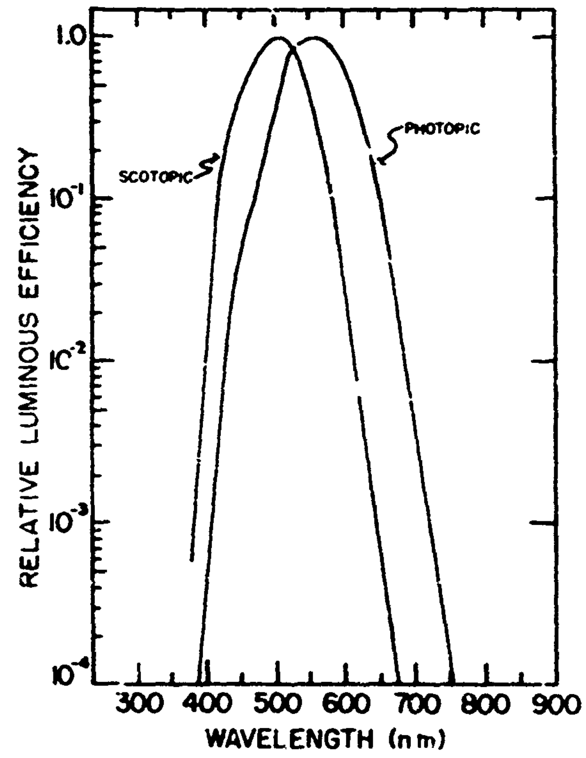

Figure 3. The CIE Visual Sensitivity Function of the Eye for Daylight Conditions (Photopic) and Nighttime Conditions is shown at left. The relative spectral transmittances of several protective filters of military interest are shown for comparison in the right-hand panel.

6. LASER FILTER DAMAGE THRESHOLD (MAXIMUM IRRADIANCE). At very high beam irradiances filter materials which absorb the laser radiation are damaged, thus it becomes necessary to consider a damage threshold for the filter. Typical damage thresholds from q-switched and mode-locked pulsed laser radiation fall between 10 and 100 Joules·cm^{-2} for absorbing glass, and 1 to 100 Joules·cm^{-2} for plastics and dielectric coatings. Irradiances from CW lasers which would cause filter damage are in excess of those which would present a serious fire hazard, and therefore, need not be considered, i.e. personnel should not be permitted in the area of such lasers. Figure 4 shows examples of damage to laser filters from intense laser beams. Generally, only surface effects are noted, and little change in optical density results. Plastic materials melt superficially, glass surfaces craze, and dielectric coatings vaporize.

(A)

(B)

(C)

Figure 4. Damage to a dichroic coating (a) on a filter is normally in the form of pin holes created at 1-10J·cm^{-2}. Damage to glass; (b) is in the form of surface fractures at 10-1000J·cm^{-2}. Damage to plastic is typically surface

7. FILTER CURVATURE. If curved protective filters are required for personnel in a laser target area, personnel in the vicinity of the laser and elsewhere would not also require eye protection. Potentially hazardous specular reflections can exist to significant distances due to the preservation of the beam's collimation from flat-lens surfaces as can be seen in Figure 5. Hence, the curved filters are far more desirable than flat lens filters. The use of the standard six-diopter curvature on spectacle lenses also reduces visual distortion.

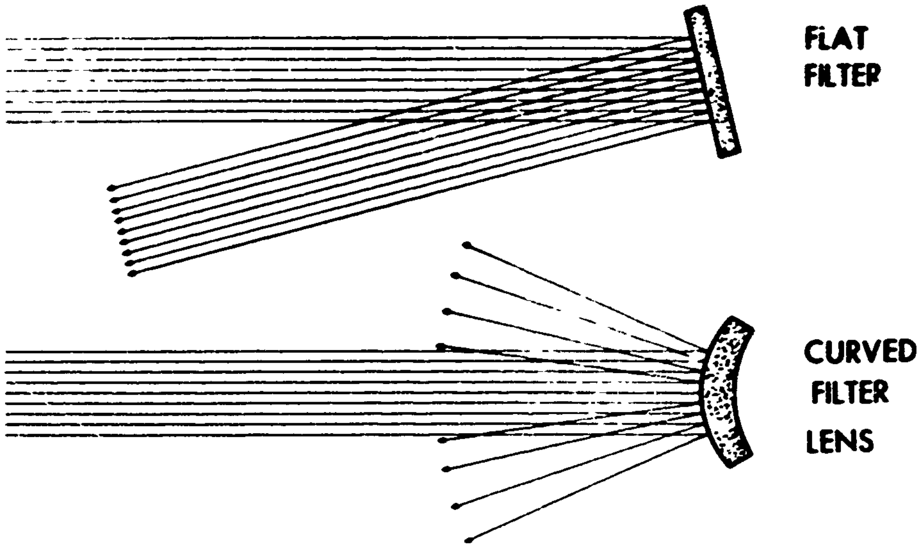

FIGURE 5. The Specular Reflection of a Collimated Beam from a Flat Surface Retains its Collimation but from a Curved Surface Diverges.

8. METHODS OF CONSTRUCTION

a. There are basically two effects which are utilized to selectively filter out laser wavelengths. Filter are designed to make use of selective spectral absorption by coloured glass or plastic, or selective reflection from dielectric coatings on glass, or both. Each method has its advantages.

b. The simplest method of fabrication is to use coloured glass absorbing filters which are generally the most effective in resisting damage from wear and from very intense laser sources. The inorganic colourants in glass are quite stable. Unfortunately, not all absorbing filters can be readily case hardened to provide impact resistance, and clear plastic sheets have often been placed with the filter. Absorbing-type filters are not always available which have sharp transmission "cut-off" near laser wavelengths in the visible.

c. The advantage of using reflective coatings is that they can be designed with relatively sharp spectral "cut-offs" to selectively reflect a given wavelength while transmitting as much of the rest of the visible as possible. However, some angular dependence of the spectral attenuation factor is generally present. Hence, dichroic coatings are used generally only in conjunction with absorbing filters, or in small field-of-view optical instruments. At present, I think this type of filter is most desirable for binoculars and telescopes. The advantages of using absorbing plastic filters materials are: greater impact resistance, lighter weight, and ease of molding into curved shapes. The disadvantages are: they are more readily scratched, quality control appears to be more difficult, and the organic dyes used as absorbers are more readily affected by heat and ultraviolet radiation and may saturate or bleach under q-switched laser irradiation. In my laboratory we encountered a number of plastic filters that undergo reversible bleaching. For example, a blue plastic filter had an optical density of 6.0 for CW 694.3 nm radiation, but only had a density of 3 for a 30 ns laser pulse. Most of these problems have been solved for the plastic laser eye protection that is now commercially available, and one need only worry that some plastics will become denser with age causing the visual transmittance to be reduced.

9. SELECTING APPROPRIATE EYEWEAR. I like to follow a step-by-step method for selecting eye protection.

STEP I. Determine Wavelength(s) of Laser Output

STEP II. Determine Required Optical Density. Table 1 lists required optical densitites (or alternatively, dB of attenuation, or attenuation factors) for various laser beam intensities which could be incident upon safety eyewear. To determine the maximum incident beam intensity, consider the following:

a. If the emergent beam is not focused down to a smaller spot, and is greater than 7-mm in diameter, the emergent beam radiant exposure/irradiance may be considered the maximum that could reach the unprotected eye, and is thus used in Table 1.

b. If the emergent beam is focused or viewed through a telescope system or if the emergent beam diameter is less than 7-mm in diameter, one should assume that all of the beam energy/power could enter the eye. In this case, you divide the laser output energy/power by the maximum area of the pupil (approximately 0.4 cm^2). This equivalent radiant exposure or irradiance may be used in Table 1.

c. If the observer is in a position where he cannot receive the maximum output radiant exposure/irradiance, then a measured value may be used. This is typical for personnel "downrange" from the laser beam.

d. In general, having an optical density in excess of one density unit above the minimum requirement is not desirable since the visual transmittance may be sacrificed. Additionally, it may be required to view the laser beam of a CW laser for alighnment; e.g. a 1 watt argon laser could be safely worked with using goggles with only a density of 3.5 to 4 which would permit momentary viewing of the direct beam -- although intentional direct viewing is not advisable.

STEP III. Determine Filter Damage Possiblity. If the maximum pulsed radiant exposure to the eye protection filter or frame exceeds $1 J\cdot cm^{-2}$ then damage to the goggle could occur. Glass filters are most desirable for protection against such exposures. At these levels skin protection must also be developed.

STEP IV. Visual Transmittance. Poor visual transmittance and reduced colour contrast as well as reduced peripheral vision in some goggles must be weighed against the benefits of the goggle. In combat environments, the added risks of wearing many types of eye protection are too great to warrant their use unless a very high probability of exposure to the direct beam exists.

10. COMMERCIAL SOURCES OF LASER EYE PROTECTION. At present no standard anti-laser goggle for the US military services has been produced. However, a variety of commercially available eye protection exists. Table II presents the optical densities at principal laser wavelengths and for actinic ultraviolet radiation (0.2 - 0.32 μm) for several types of commercial eye protection of which I am most familiar in the United States.

11. TESTING LASER EYE PROTECTION. Eye protection should be checked periodically for integrity. The measurement of eye-protection-filter optical densities in excess of 3 or 4 without destruction of the filter is very difficult[13]. Because of this problem, requirements originally proposed for many laser hazard control guidelines, that the optical density of protective eyewear be periodically checked, have been deleted. The greatest concern has been with goggles having specified optical densities at or only slightly above the density required for protection. Normally, required densities do not exceed 8. Goggles having densities less than 8 are normally designed for use at either the helium-neon or ruby laser wavelengths. Therefore, if a more comprehensive goggle testing program were initiated, the goggles which should receive first attention are those having a density less than 6 for the ruby and helium-neon lasers. My associates and I have periodically checked the optical density of various types of commercial eye protection. In general, the goggles met or exceed specifications given by the manufacturer and listed in Table II. However, in some rare instances protection filters were shown to have densities less than specified. In one case, the lower density still exceeded 8 and was therefore not of concern. In a second case, the density was significantly less than a specified density of 6. At present, all evidence indicates that the optical density of commercially available eyewear does not decrease with use although some plastics become slightly more dense after considerable exposure to solar radiation and due to aging. The actual measurement of filter optical densities between 3 and 10, and perhaps greater densities, can be performed with special techniques using either a spectrometer or laser. As noted previously, spectrophotometers found in most chemical laboratories are limited to measurements of densities 2 to 3. This limitation arises from difficulties from "stray light" passing through the monochrometer[14]. Stray light arises principally from dust and microscopic imperfections in the prisms or diffraction gratings which scatter light of wavelengths other than the 1 wavelength of interest. Obviously, this stray light can be greatly reduced by placing monochrometers in tandem or by using narrow-band filters (see Figure 6). However, measurement problems arise after one achieves a far more pure monochromatic beam if the detector does not have sufficient sensitivity. Unless a laser is used as the light source, the bandwidth (slitwidth) of the monochrometer may be so increased to achieve a measurable signal at the detector that a braod-band attenuation factor is measured for the protective filter--a very serious shortcoming for filters having a rapidly changing optical density with changing wavelength. The use of lasers to measure filter transmission is unfortunately limited to the wavelengths of the lasers available. The laser method also required the use of narrow-band (laser "spike") filters (Figure 5) to eliminate pump light from optically pumped lasers or the glow discharge from gas lasers. Measurement errors can arise if the laser output is not uniformly stable. One advantage of using a Q-switched (~20 ns pulse) or mode locked (10-10 ps) pulsed laser is that reversible bleaching that can occur, particularly in organic dyes used in plastic filters may be detected.[15]

12. MARKING OF EYE PROTECTION. The optical density at appropriate laser wavelengths should be marked on the eye protection, since the use of goggles designed for one laser have been mistakenly used with another laser and could have resulted in ocular injury. Less technical marking, for example "use only with ruby laser", may also be desirable for field equipment.

***TABLE I.* Selecting Laser Safety Glass**

CW laser			Non-Q-switched laser		Q-switched laser		Attenuation		
Maximum irradiance ($W \cdot cm^{-2}$) (momentary viewing)	Maximum irradiance ($W \cdot cm^{-2}$) (continuos staring)	Maximum output power (W) (continuous staring)	Maximum radiant exposure ($J \cdot cm^{-2}$)	Maximum output energy (J)	Maximum radiant exposure ($J \cdot cm^{-2}$)	Maximum output energy (J)	OD	dB attenu-ation	Attenu-ation factor
4×10^{-3}	10^{-5}	4×10^{-6}	10^{-6}	4×10^{-7}	10^{-7}	4×10^{-8}	1	10	10
4×10^{-2}	10^{-4}	4×10^{-5}	10^{-5}	4×10^{-6}	10^{-6}	4×10^{-7}	2	20	10^2
4×10^{-1}	10^{-3}	4×10^{-4}	10^{-4}	4×10^{-5}	10^{-5}	4×10^{-6}	3	30	10^3
4	10^{-2}	4×10^{-3}	10^{-3}	4×10^{-4}	10^{-4}	4×10^{-5}	4	40	10^4
40	10^{-1}	4×10^{-2}	10^{-2}	4×10^{-3}	10^{-3}	4×10^{-4}	5	50	10^5
	1.0	4×10^{-1}	10^{-1}	4×10^{-2}	10^{-2}	4×10^{-3}	6	60	10^6
	10	4.0	1.0	4×10^{-1}	10^{-1}	4×10^{-2}	7	70	10^7
			10	4.0	1.0	4×10^{-1}	8	80	10^8

TABLE II

[illegible]

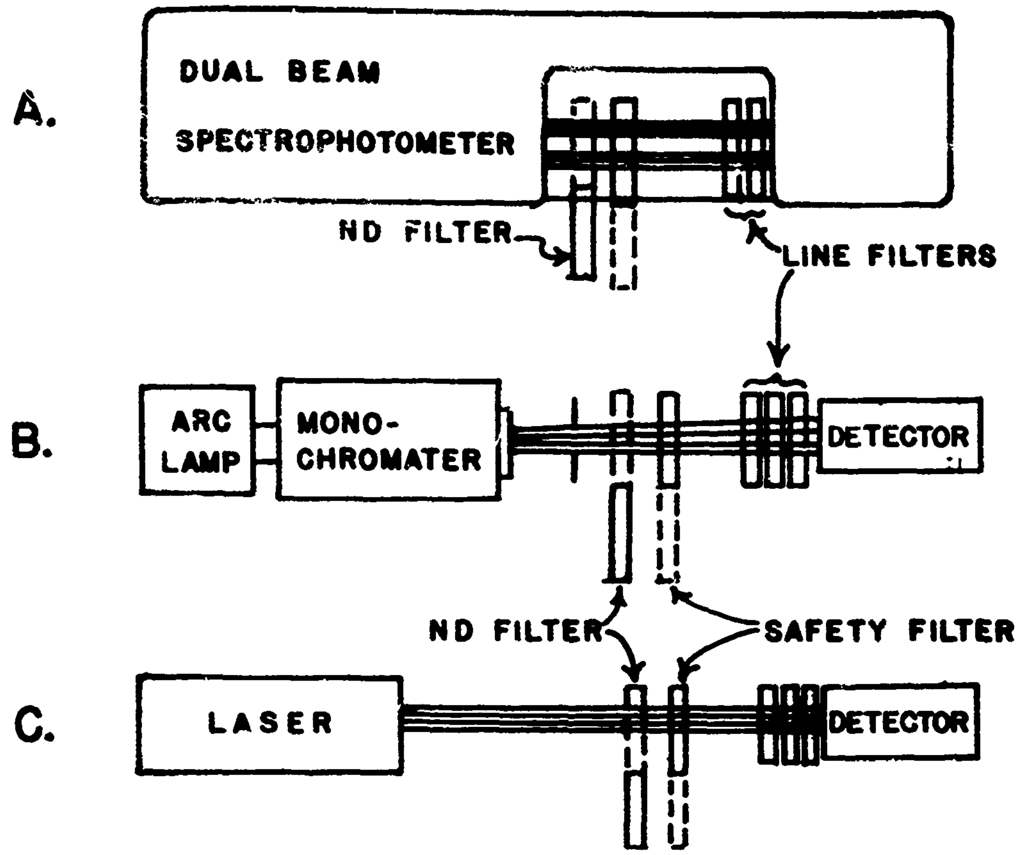

FIGURE 6. Three methods used for direct measurement of laser filter transmission are shown; several other variations of combinations of filters light sources and monochromators are possible. In all arrangements, one or more neutral density filters calibrated at the wavelength of interest are inserted in place of the protection filter until the transmission comparison is within 1 OD unit. This procedure is necessary to reduce errors for detector non-linearity. Laser line filters are continuously added in series until the addition of filters (the reduction in unwanted light of other wavelengths).

13. EYE PROTECTION FOR INFRARED LASERS.

a. Optical radiation at wavelengths greater than 1.4 µm is absorbed in the anterior proortion of the eye and does not reach the retina. Protection standards for both the eye and skin have normally been of the same value. The need for skin protection as well as eye protection is therefore, necessary to consider. Protection of the eye is nonetheless of paramount importance, since an injury to the eye (specifically the corneal stroma in most instances) can result in total or partial blindness, whereas the skin burn from a comparable laser dose would heal without such a disability.

b. Most optical materials which are transparent in the visible spectrum (transparent plastics, glass, and quartz) are essentially opaque at wavelengths greater than 4.8 µm. All of these materials are therefore used for eye protection for CO (5µm) and for CO_2 (10.6 µm) laser radiation. Plastic goggles are preferred for protection against a low-probability of exposure reflections from CO_2 lasers naving an output power less than 100 W despite the fact that the plastic may burn. Quartz (e.g. AO Model 300) or heat-resistance glass (e.g. Hadron Type 112-4) goggles worn in conjunction with face shields and skin protection have been used when high-power CO_2 laser beams cannot be enclosed.

c. Eye protection at wavelengths less than 5 µm has become a problem at certain wavelengths where Lucite®, Plexiglass® and lime glass do not have absorption bands. The better approach used in the radiometry laboratory for an all purpose filter for wavelengths greater than 1.4 µm is a water cell. Because of weight and other design problems the H_2O filter has not been considered practical eye protection method outside of a laboratory window. Although water goggles have been made[16], more practical, lightweight goggles may be fabraicated by using 3 to 5 mm Schott KG-3® glass filters which provide an OD of 3 to 5 at the deuterium-fluoride laser wavelengths of 2.7 - 3.0 µm and at the hydrogen fluoride laser wavelengths of 2.9 - 3.2 µm.

14. EYE PROTECTION FOR PUMP LAMPS AND TUNABLE WAVELNGTH LASERS.

a. Occasionally eye protection is necessary to work with exposed arc lamps used as optical pumping sources for pulsed or CW lasers. Eye protection developed for welding is quite suitable for this purpose. Likewise, some dye lasers may be scanned over most of the visible spectrum, and welding goggles may provide the only solution to some viewing requirements.

b. Eye protection filters for welders were developed empirically; however, optical transmission characteristics are now standardized as "shades" and spcified for particular applications.[17 18] Although maximum transmittances for ultraviolet and infrared radiation are specified for each shade, the visual transmittance τ_v or visual optical density D_v defines the shade number S#

$$S\# = 7/3\, D_v + 1 \quad (5)$$

Where

$$D_v = -\log_{10} \tau_v \quad (6)$$

For instance, a filter with a visual attenuation factor of 1000 (i.e., $D_v = 3$) has a shade number of 8. Electric arcs typically have luminances of the order of 10^4 to 10^5 $cd \cdot cm^{-2}$ and filter densities ranging from 4 to 5 corresponding to shades 10 to 13 are required for comfortable viewing.[19] Likewise, a shade of at least 13 is required to view the sun which has a luminance of approximately 10^5 $cd \cdot cm^{-2}$. These densities are far in excess of those necessary to prevent retinal burns, but are required to reduce the luminance to 1 $cd \cdot cm^{-2}$ or less for viewing comfort. The user of the eye protection should therefore be permitted to choose the shade most desirable to him for his particular operation. Actinic ultraviolet radiation from quartz-enclosed arcs is effectively eliminated in all standard welding filters.

15. POLARIZING FILTERS. At first thought, the use of polarizing spectacles appears appealing as eye protection for multiple-wavelength use, since many lower output beams are highly polarized. Unfortunately, optical densities above two can scarcely be achieved, and a tilt of the head would render the protection almost non-existent. Nevertheless, such filters are often useful in a rotatable mount at the laser exit port as a means of reducing the output to a reasonable safe level for alignment purposes in many laboratory arrangements. Rotatable, cross-polarizing filters have occasionally been mounted in eyewear to work with variable light sources, but their use is limited since commercially available polarizing sheet material is effective in a limited band of wavelengths, and while densities up to at least 2, may exist in the visible spectrum, potentially hazardous levels of near-infrared radiation could pass through the filters.

16. DYNAMIC EYE PROTECTION DEVICES. Numerous dynamic systems have been studied as eye protection against pulsed optical sources such as the nuclear fireball. The ideal dynamic filter is nearly transparent except when activated by a hazardous light source, at which time it rapidly becomes nearly opaque for the duration of the light flash. These systems usually consist of photo-detector-actuated shutters (which may be mechanical, electro-optic, or magneto-optic) or photoreactive filters (such as photochromic materials). These devices are generally rather cumbersome when compared with typical laser safety goggles or welder's goggles. Dynamic filters generally offer the only practical solution for eye protection against unexpected white-light (broad-band) pulsed sources; however, this appraoch has not been require in the development of laser eye protection, since sharp cutoff filters which attenuate the laser wavelength also transmit sufficient light for vision. Additionally, dynamic filter devices are not presently capable of achieving significant optical densities even within 10 μs which is far greater than the duration of typical q-switched laser pulse (~20 ns), although such a fast response is theoretically possible.[20-25] Image converter viewers designed to view near-infrared radiation and as night-vision viewing devices can serve as laser protective eyewear. Although the image converter tubes may be damaged by direct laser irradiation, these devices provide equivalent optical densities of at least 8 for all wavelengths. Their disadvantage is bulkiness and monochromatic presentation with some loss of resolution of the objects being observed.[25]

17. FUTURE DEVELOPEMNTS.

a. It is difficult to predict future developments in laser technology. In the future, more laser systems will be available in the infrared, and improvements may be expected in infrared detectors. It appears reasonable that present laser applications which require unenclosed lasers (e.g. laser distance measurement equipment), but do not require a visible beam (as do alignment lasers) may best be realized by using an infrared laser operating in the relatively "eye-safe" region beyond 1.4 μm.

b. National safety codes being developed will probably encourage the manufacturing of enclosed laser systems, and lasers which required the use of eye protection will probably be limited largely to the military and research environment.

c. It is technologically feasible that new filter materials could be developed which have narrower absorption bands in the vicinity of a laser wavelength. Such a development would be more likely to be in a plastic material rather than in a glass. Interference filter coatings sealed between layers of absorbing plastic now show promise.

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BIBLIOGRAPHY ON LASER HAZARDS AND SAFETY IN THE MILITARY ENVIRONMENT

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CONTENTS

INTRODUCTION

This bibliography has been compiled by the Defence Research Information Centre to provide literature references to the problems of hazards and safety in the use of lasers in support of the AGARD Lecture Series No. 79 - "Laser Hazards and Safety in the Military Environment". The programme of this lecture series is related to laser radiations and the nature of ocular damage from laser radiation, protection against lasers, implications of safety codes, the opthalmic examination of laser workers, and investigation of accidents.

The bibliography has been compiled using the ESRO RECON information network terminal at DRIC and is based upon the NASA/STAR-IAA file.

The references are of items announced in the period 1970-1974.

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General Review Papers

1 74A19542 ISSUE 07 CATEGORY 16 000073
APPLICATIONS OF THE LASERS --- BOOK
Goldman, L.
Cleveland, CRC Press, Inc., 1973. 315 p. AA(Cincinnati, University, Cincinnati, Ohio) REFS.522 *26
*BIOTECHNOLOGY/ CHEMICAL LASERS/ DENTISTRY/ DIAGNOSIS/ ENVIRONMENT POLLUTION/ *HOLOGRAPHY/ LASER MATERIALS/ *LASERS/ *MEDICAL EQUIPMENT/ METAL WORKING/ MILITARY TECHNOLOGY/ *OPTICAL COMMUNICATION/ PHOTOGRAPHIC RECORDING/ RADIATION HAZARDS/ SAFETY FACTORS/ *TECHNOLOGY UTILIZATION/ THIN FILMS

2 72A21333 ISSUE 08 CATEGORY 05 000971
THE BIOEFFECTS OF LIGHT. (BIOLOGICAL HAZARDS OF HIGH INTENSITY LIGHT SOURCES, CONSIDERING PHYSIOLOGICAL FACTORS INVOLVED IN THRESHOLD EYE DAMAGE VALUES DETERMINATION.)
Van Pelt, W.F.; Payne, W.R.; Stewart, H.F.; Peterson, R.W.
Optical Spectra, Vol. 5, Sept. 1971, p. 33-36. AD(U.S. Department of Health, Education, and Welfare, Food and Drug Administration, Washington, D.C.) REFS. 8
*BIOLOGICAL EFFECTS/ *EYE (ANATOMY)/ INFRARED RADIATION/ LASER OUTPUTS/ *LIGHT SOURCES/ *LUMINOUS INTENSITY/ *RADIATION DAMAGE/ TISSUES (BIOLOGY)/ ULTRAVIOLET RADIATION

3 72A17945 ISSUE 06 CATEGORY 16 000071
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Safety and Hazard Analysis

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